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Controlled Wave-Particle Interaction and VLF Wave Propagation Experiments in the Outer Magnetosphere

H. C. KOONS
Space Sciences Laboratory
Laboratory Operations
The Aerospace Corporation
El Segundo, Calif. 90245

15 June 1981

Interim Report

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This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

Randall Scott Weidenheimer

Randall S. Weidenheimer, 2nd Lt, USAF
Project Officer

Florian P. Meinhardt

Florian P. Meinhardt, Lt Col, USAF
Director of Advanced Space Development

FOR THE COMMANDER

William Goldberg

William Goldberg, Colonel, USAF
Deputy for Technology

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VLF transmission experiments were conducted from sites in North Norway during selected time periods in 1978, 1979 and 1980. Data from these experiments were collected from VLF receivers aboard the SCATHA (P78-2) and GEOS satellites and VLF receivers on the ground at various locations in Norway and Sweden. Direct signals were measured at each of the ground stations and emissions triggered by the transmissions were detected by the satellite receivers. This report documents the impedance measurements made on each of three power lines

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19. KEY WORDS (Continued)

20. ABSTRACT (Continued)

used as VLF antennas and summarizes the preliminary results from the VLF receiver data.

PREFACE

This report, which documents research carried out from 1 January 1978 to 30 September 1980 is issued by The Aerospace Corporation, El Segundo, California. The research was supported in part under NSF Grant ATM-77-19361.

This NSF grant provided partial support for VLF transmission experiments conducted from Sortland, Norway from 27 September to 4 October 1978; and from Kafjord, Norway from 4 August to 11 August 1979 and 20 July to 27 July 1980. It also provided partial support for the reduction and analysis of data from these campaigns and additional transmission experiments conducted by Prof. M. Garnier of the University of Paris.

Data from these experiments were collected from VLF receivers aboard the SCATHA (P78-2) and GEOS satellites and VLF receivers on the ground at various locations in Norway and Sweden. Direct signals were measured at each of the ground stations and emissions triggered by the transmissions were detected by the satellite receivers. The data will be used to assess the importance of power line radiation in the outer magnetosphere.

Support from a preceding NSF Grant ATM-75-18118 was used to assess the feasibility of using a power transmission line on Andoya Island, Norway as an antenna for the TVLF Transmitter. Since that work related to this grant the results are included in this report.

Mr. Mitchell Dazey of The Aerospace Corporation has been the principal engineer on the TVLF programs. His innovative solutions to technical problems in the field has materially contributed to the success of these experiments.

The initial impetus to use the TVLF transmitter in Scandinavia was provided by Dr. Arne Pedersen of ESTEC. The Space Activity Division of the Royal Norwegian Council for Scientific and Industrial Research (NTNF) was particularly helpful with numerous negotiations and arrangements with Norwegian agencies. We are especially indebted to Prof. Jan A. Holtet of the University of Oslo who devoted many months helping in the field, and working with the local and national agencies to insure success in the transmissions, to Prof. Les Wooliscroft, University of Sheffield, who was able to inspire a number of agencies to help us financially, and in addition, made the ground calibration measurements for the 1980 campaign and to R. G. Robbins, R. L. Walter, and J. Døhl who worked hard to overcome all of the equipment failures and keep the transmitter on the air. We wish to thank Prof. M. Garnier, G. Girolomi and J. Conrad, University of Paris, who made measurements and transmissions which were helpful in designing components for the larger transmitter, and demonstrated a transmission line configuration that would not cause telephone interference.

CONTENTS

FIGURES

TABLE

1.0 INTRODUCTION

In 1976 scientists from the European community expressed an interest in transmitting ELF signals to the GEOS satellite using the Aerospace Corporation's TVLF transmitter facility and a 21.3-km long power line in Norway as the antenna. The line normally carries 60 kV of three-phase power on the island of Andoya near the town of Andenes, Norway. Since The Aerospace Corporation also provided a VLF receiver for the P78-2 (SCATHA) satellite this provided a unique opportunity to study wave-particle interactions and whistler-mode propagation in the outer magnetosphere.

In the fall of 1977 Prof. M. Garnier of the University of Paris and Mr. M. Dazey of The Aerospace Corporation made impedance measurements on the Andoya line. The results, reported in Aerospace Report No. ATR-78(7578)-1 (Appendix A), are summarized in Section 2.1.

Prof. Garnier attempted transmissions to GEOS using a 1-kW transmitter and the Andoya line. Problems with a backup line caused the power company to suggest an alternate line, the Sortland Line. This line ran about 34 km between the towns of Strand and Konstadbotn. It was a "standby" line that was only required when it was necessary to service an operating line. Impedance measurements were performed on this line in September 1978. Test transmissions with the TVLF transmitter were begun on 27 September 1978.

The impedance measurements, reported in Aerospace Report No. ATR-79(7731)-1 (Appendix B), are summarized in Section 2.2. Telephone interference, even at low antenna currents, proved to be unacceptable and use of this line was discontinued.

A line near Kafjorddalen, Norway was tested by Prof. Garnier in the spring of 1979. After an electrical configuration change the telephone interference in the area was acceptably low and transmission experiments to SCATHA and GEOS were conducted several times throughout 1979 and 1980. The electrical measurements on this line are summarized in Section 2.3.

During each campaign in 1979 and 1980 some emissions that could be correlated with the transmission frequency were detected by the SCATHA VLF receiver. The results of the preliminary analysis of these data are summarized in Section 4.0.

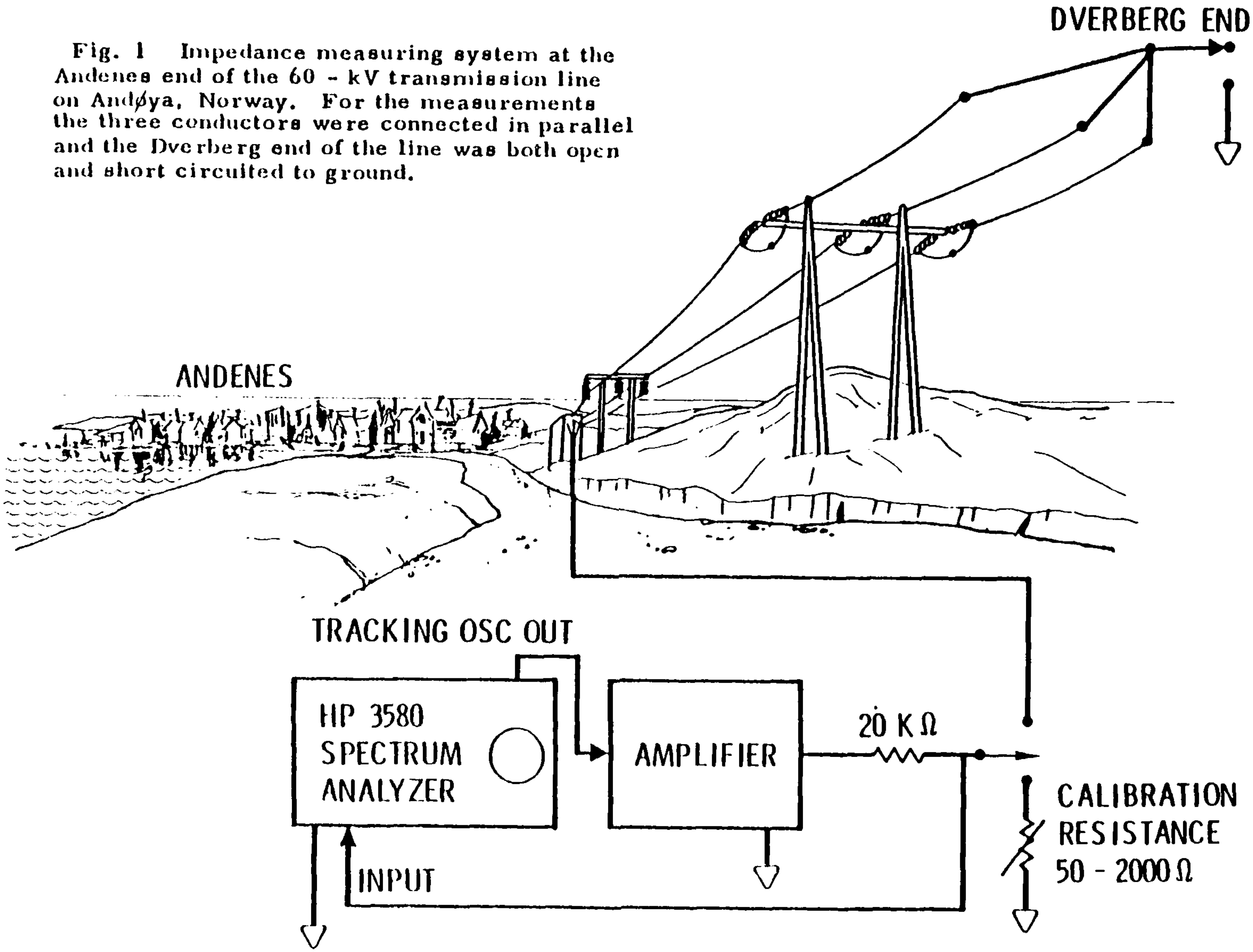
2.0 EXPERIMENT OPERATION

2.1 Andoya Island (1977). The Andoya 60-kV transmission line is 21.3 km long, and is strung over hilly terrain between Andenes and Dverberg, Norway. At the time of the impedance measurements, April 29, 1977, there was 2 to 5 feet of wet snow under most of the line. The impedance measuring system is shown in Figure 1. The open circuit impedance Z_{oc} and the short circuit impedance Z_{sc} of the line are shown in Figure 2 as a function of frequency. The line parameters were computed and are presented in the report in Appendix A. The radiation resistance at 2.6 kHz is estimated to be 0.018 ohms. In the voltage-limited mode, assuming that the power available from the TVLF system is 100 kW, the radiated power would be ~ 15 W.

In March 1978 Prof. Garnier attempted transmissions to GEOS using a 1-kW transmitter. The use of the 60-kV line required the transfer of its normal load to an older 22-kV line. The line voltage of the 22-kV line dropped approximately 20%. This undesirable effect caused the power company to suggest an alternate line, the Sortland line.

2.2 Sortland (1978). The Sortland line runs 34 km between the towns of Strand and Konstadbotn, Norway. The impedance of this line was measured using the same measuring system as shown in Figure 1. The short circuit and open circuit impedances are shown in Figures 3 and 4. The analysis of the test results, contained in the report in Appendix B, indicated that the Sortland line is not as well behaved electrically (i.e., as a uniform transmission line) as the Andoya line. The line runs approximately 1000 m from a fjord for 80% of the distance from Strand to Kanstadbotn. The final 20% is constructed over relatively mountainous terrain. If the final 20% of the line were dis-

Fig. 1 Impedance measuring system at the Andenes end of the 60 - kV transmission line on Andøya, Norway. For the measurements the three conductors were connected in parallel and the Dverberg end of the line was both open and short circuited to ground.



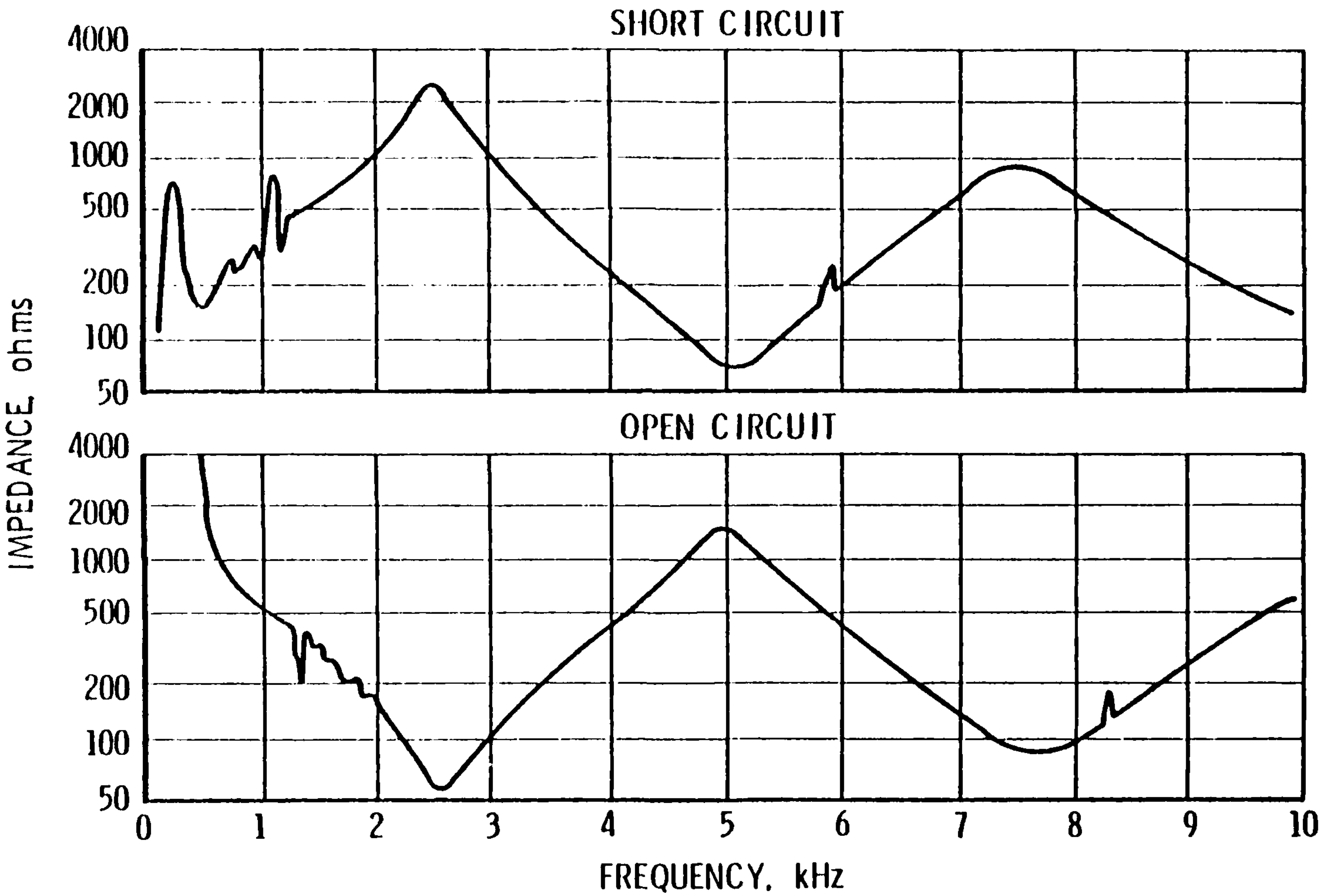


Fig. 2 Short circuit impedance Z_{sc} and open circuit impedance Z_{oc} of the Andøya line as a function of frequency. Second data set covering 0 - 10 kHz.

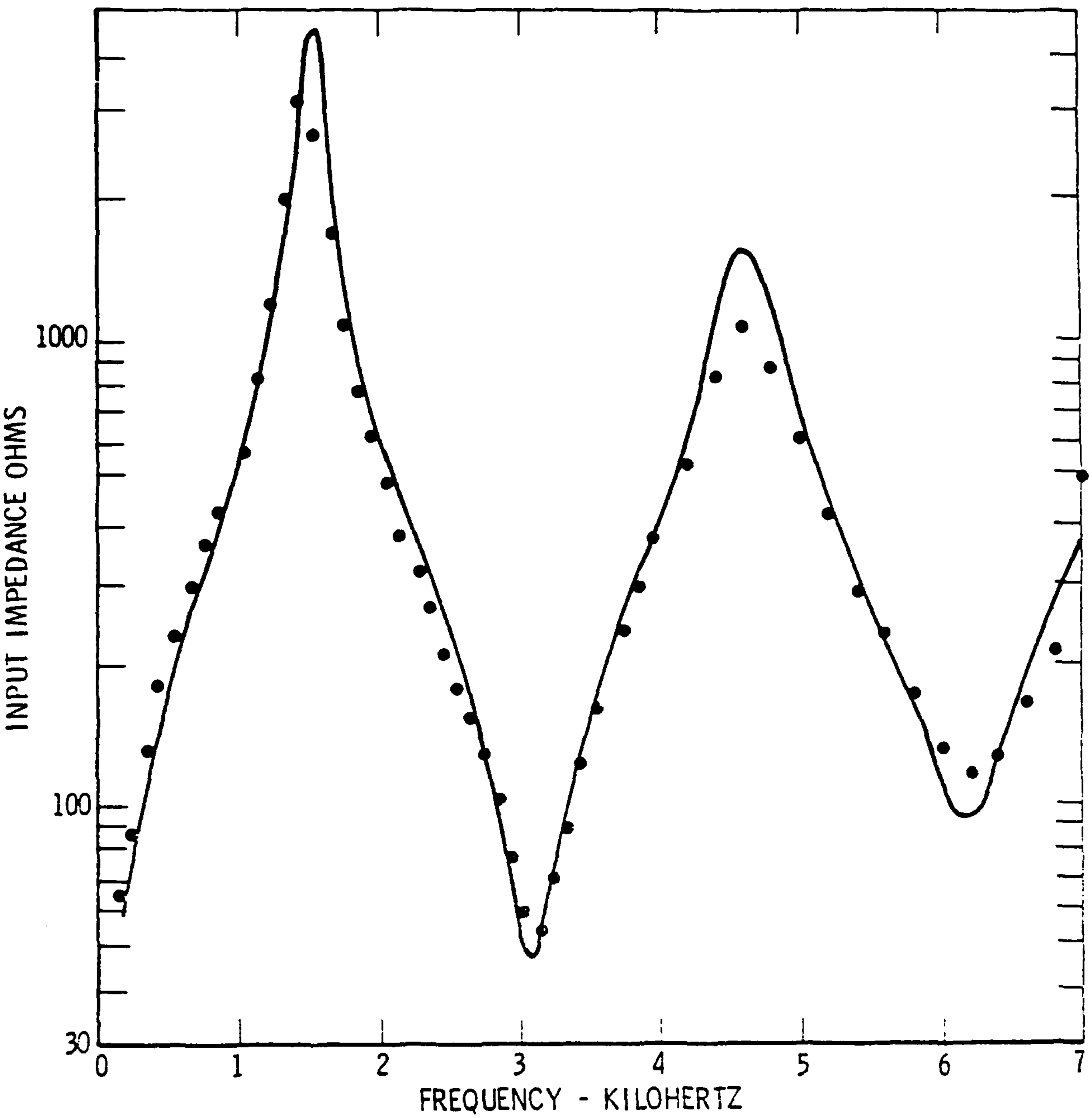


Fig. 3 Input impedance vs frequency. Sortland line with Short Circuit.

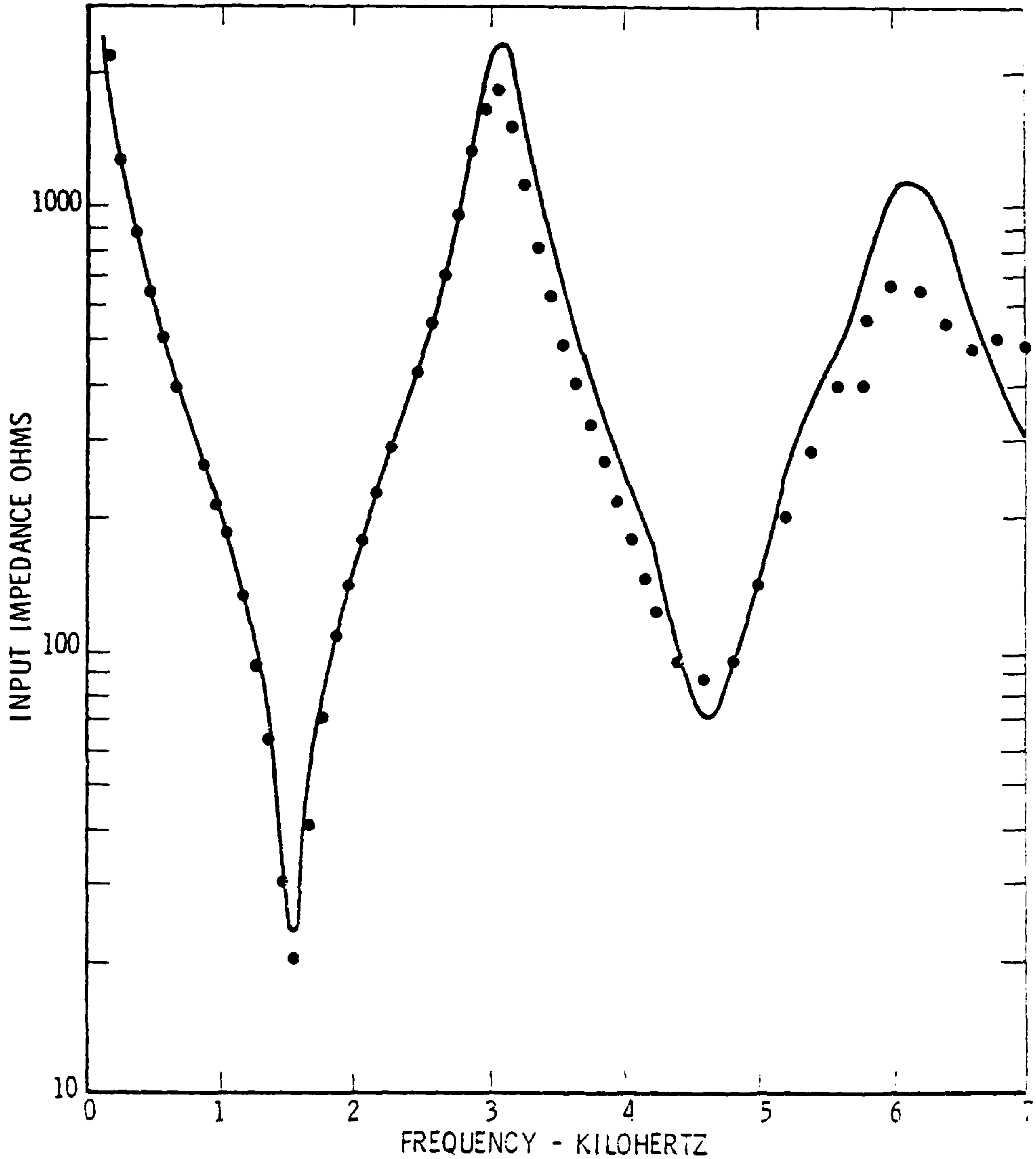


Fig. 4 Input impedance vs frequency. Sortland line with Open Circuit.

connected it would be expected to resonate at harmonics of 7 kHz. Significant perturbations in the impedance curves start at approximately that frequency.

The line parameters were computed and are presented in the report in Appendix B. The radiation resistance was estimated to be 0.0067 ohms and the radiated power 10 W.

During the test transmissions by the TVLF transmitter there were several reports of the signal being picked up by telephones close to the transmission line. Several tests conducted between 27 September and 4 October 1978 demonstrated that the interference (even at a low antenna current of 5 A) was unacceptable.

Some transmissions were conducted in conjunction with GEOS data acquisitions. Prof. Garnier has examined these data and reports that there is evidence of the direct TVLF signal being detected by GEOS.

2.3 Kafjord (1979-1980). The Kafjord line runs 14 km between Kafjorddalen and Lake Guolasjav'ri. The line runs up a mountain from sea level to 800 m.

Initial tests caused unacceptable interference at the telephone switchboard in Birtavarre near the Kafjorddalen end of the line. Since the residences were all close to the transmitter end of the line, a test was made with the first 3.6 km of the line 'floating' above ground. This test indicated that currents above 50 amperes could be used without causing telephone interference.

The impedance of this line was measured using the same measuring system as shown in Figure 1. The short circuit and open circuit impedances are shown in Figs. 5 and 6. The analysis of the line parameters are presented in the report in Appendix C. The radiation resistance using inductive tuning in 198[illegible]

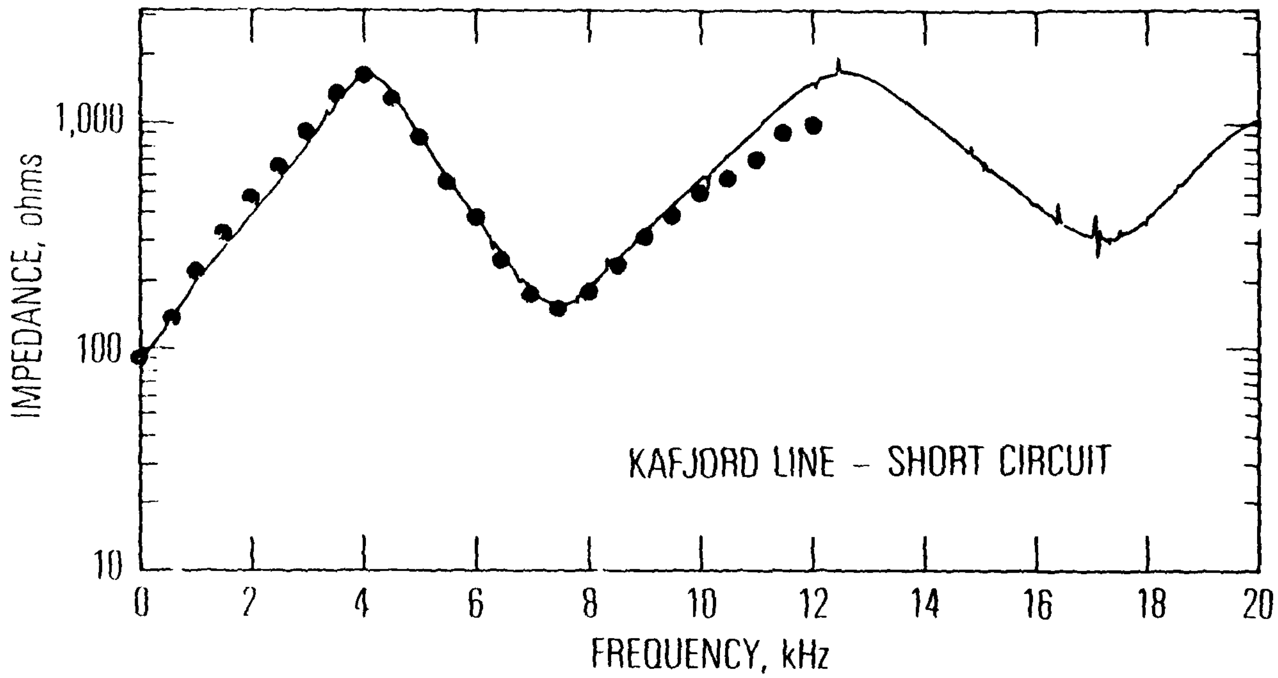


FIG. 5. Short circuit impedance of the Kafjord line.

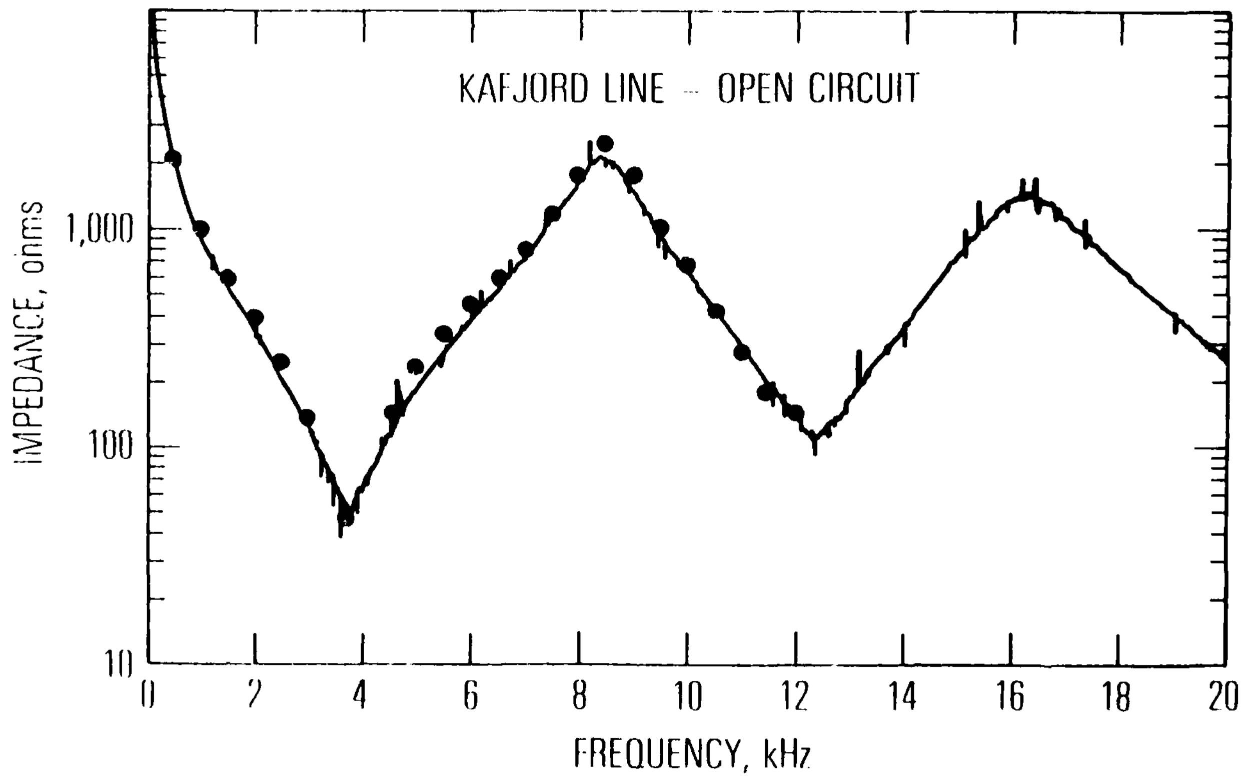


FIG. 6. Open circuit impedance of the Kafjord line.

was estimated to be 0.018 ohms at 1280 Hz. For a 40 A antenna current the radiated power would be 29 W.

The earth's conductivity derived from the impedance measurements is $\sim 10^{-5}$ S/m. This is about an order of magnitude lower than the generally accepted minimum valve for the conductivity of rock. Figure 7 shows the dependence of skin depth and radiated power on earth conductivity. An independent estimate of radiated power will be made when the field strength measurements made by personnel from the University of Sheffield are made available to us.

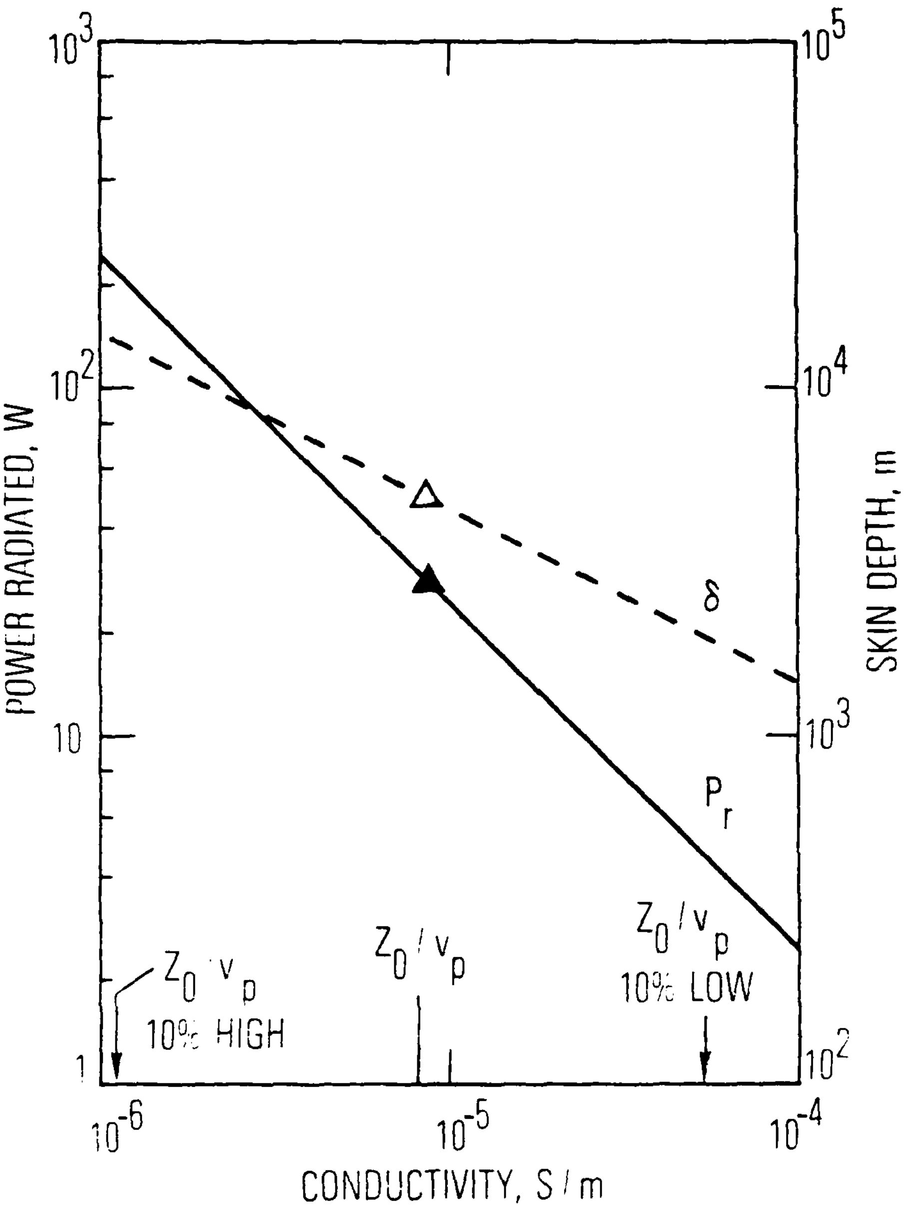


FIG. 7. Power radiated, P_r, and skin depth, δ, at 1280 Hz as a function of rock conductivity. The triangles are the result of the measurements and calculations reported here. The conductivity for 10% errors in Z_0/v_p are also indicated.

3.0 DATA BASE

Table 1 contains a summary of the transmission campaigns and the SCATHA data collected near the Kafjord magnetic meridian. All of the data with the exception of the October 1980 data has been reduced to spectrograms. Tapes and duplicate spectrograms have been provided to the University of Paris for their analysis.

Table 1. Satellite Data Base

Dates	Location	Organization	SCATHA Broadband Data
9/27 - 10/4/78	Sortland	Aerospace	(GEOS)
5/25 - 6/1/79	Kafjord	U. of Paris	11.5 hrs
8/4 - 8/11/79	Kafjord	Aerospace	8.6 hrs
5/10 - 5/17/80	Kafjord	U. of Paris	10.7 hrs
7/20 - 7/26/80	Kafjord	Aerospace	22.8 hrs
10/1 - 10/9/80	Kafjord	U. of Paris	17.3 hrs
		Total	70.9 hrs

Prof. Les Woolliscroft, University of Sheffield, made ground-based ELF measurements at Lavangsdalen near Tromso, Norway and at Luonattivagen near Kiruna, Sweden. These field intensity measurements will be used to estimate the power radiated by the antenna.

4.0 DATA ANALYSIS

Emissions correlated with the transmissions from Kafjord were recorded by the SCATHA receiver on several days during the various campaigns. The transmissions consisted either of a keyed fixed frequency or a continuous wave swept in frequency. With the first type of transmission narrowband emissions starting very near the transmitter frequency were detected on May 27, 1979; August 6, 1979; and July 25, 1980. An example is shown in Figure 8. Four examples of falling-tone discrete emissions are also likely to have been triggered.

Both types of transmissions triggered or enhanced hiss at a constant frequency during fixed frequency transmissions and at a variable frequency in another case. During swept frequency transmissions there occurred two examples natural emissions shifting in frequency by the man-made signal.

An unusual observation occurred on August 6, 1979 when an electron cyclotron harmonic emission also appeared to have been shifted in frequency by the man-made signal. The frequency of this emission is shown as a function of time in Figure 9. Near 1730 UT and near 1750 UT the emission frequency appears to be captured by the TVLF transmitter frequency, 1280 Hz. For a short time near 1730 UT the spectrum (shown in Fig. 10) is quite unique. The emission splits into two narrower lines which are reasonably monochromatic and span the local electron gyrofrequency.

The analysis of these results is continuing. Prof. Garnier has presented preliminary results at the COSPAR meeting in Budapest, Hungary, June 2-14, 1980 and at the Fourth Workshop on IMS Observations in Northern Europe in Issy-les-Moulineaux, France, September 22-26, 1980. The COSPAR paper is repro-

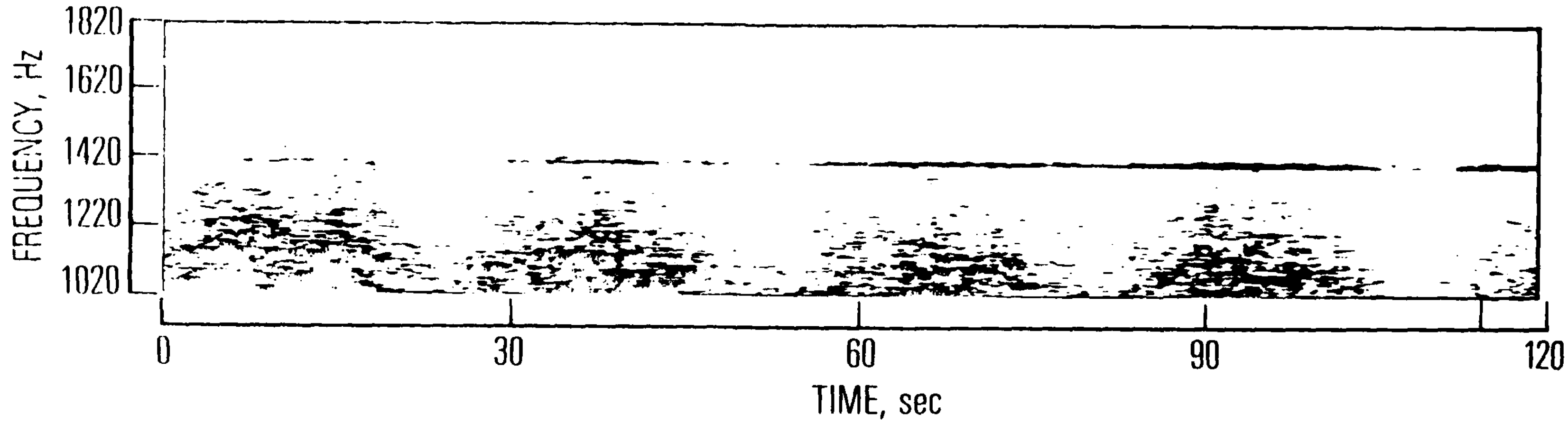


FIG. 8. Spectrogram of an ELF emission at 1420 Hz detected by the SCATHA VLF receiver shortly after the TVLF transmitter began transmissions at 1420 Hz.

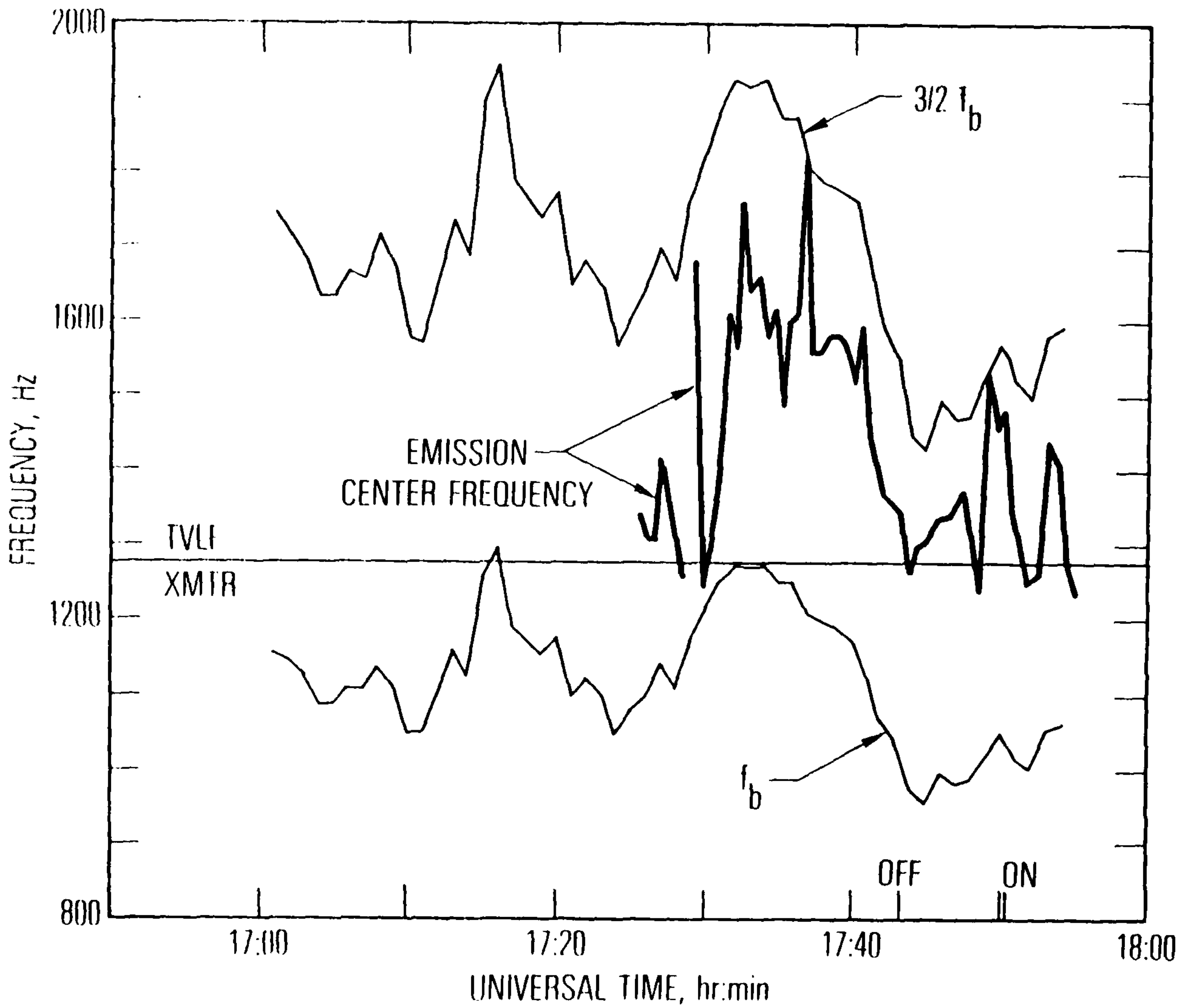


FIG. 9. Center frequency of an emission detected by the SCATHA VLF receiver during TVLF transmissions at 1280 Hz. The electron gyrofrequency, f_b, and $3/2\ f_b$ as measured by the SC11 experiment (Brian Ledley, GSFC) on SCATHA are shown for comparison.

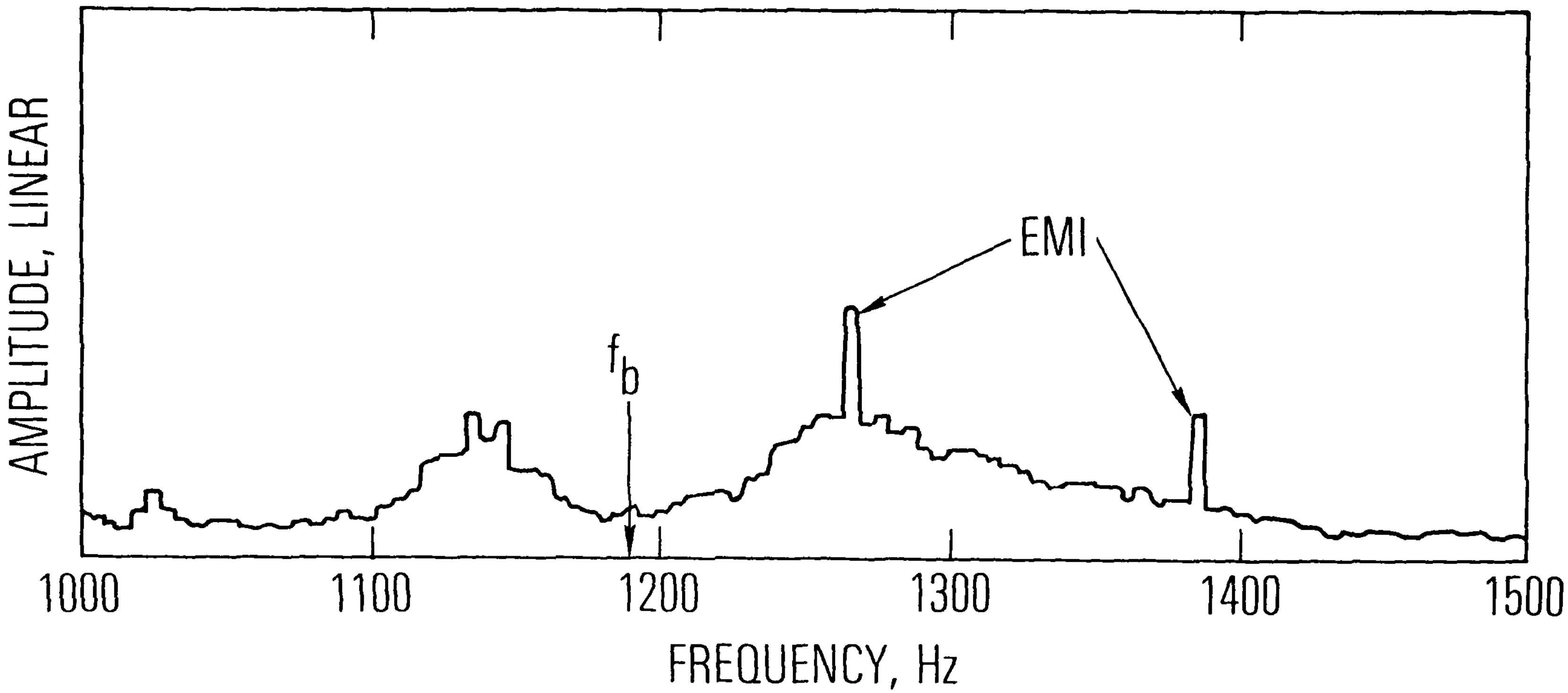


FIG. 10. Spectrum of the emission shown in Fig. 9 near 17:30 UT showing emissions below and above the electron gyrofrequency, f_b.

duced in Appendix D. Further results will be presented in an invited talk at the Magnetospheric Wave Injection Session at the 1981 URSI meeting in Washington, D.C.

Work is continuing on the analysis and interpretation of the data. Two important conclusions are: (1) that the transmitter signals are rarely (perhaps never) directly detected and (2) they do not trigger chorus type emissions. Since the radiated power is believed to be significantly higher than power line harmonic radiation it would seem that power line harmonic radiation should not be directly detected nor should it routinely produce chorus type emissions in the outer magnetosphere.

5.0 PUBLICATIONS, PRESENTATIONS AND REPORTS

The following publications, presentations and reports contain the results of the work supported in part by NSF Contract ATM77-19361 or related directly to that contract:

1. M. H. Dazey and H. C. Koons, Impedance and Radiation Resistance of the Andoya, Norway 60-kV Transmission Line, Aerospace Rpt. No. ATR-78(7578)-1, The Aerospace Corp., El Segundo, Calif., November 1977.
2. M. H. Dazey, The Sortland, Norway Transmission Line VLF Tests September-October 1978, Aerospace Rpt. No. ATR-79(7731)-1, The Aerospace Corp., El Segundo, Calif., December 1978.
3. M. H. Dazey, Kafjord, Norway Transmission Line VLF Antenna Tests, 1979-1980, Aerospace Rpt. (in preparation), 1980.
4. M. Garnier, G. Girolami, H. Koons and M. Dazey, VLF Emissions from Kafjord (Norway) to SCATHA, presented at the COSPAR Meeting, Budapest, Hungary, 2-14 June, 1980.
5. M. Garnier, G. Girolami, H. Koons and M. Dazey, VLF Transmissions from Kafjord to GEOS and SCATHA, presented at the Fourth Workshop on IMS Observations in Northern Europe, Issy-les-Moulineaux, France, 22-26 September, 1980.
6. M. Garnier, G. Girolami, H. C. Koons and M. H. Dazey, Stimulated Wave-Particle Interactions during ELF Transmission Experiments from Kafjord, Norway, manuscript in preparation for submission to the J. Geophys. Res., 1981.
7. H. C. Koons and M. H. Dazey, High-Power Transportable ELF/VLF Transmitter Facility, manuscript in preparation for submission to the Proc. IEEE.

8. H. C. Koons, M. H. Dazey, M. Garnier, and G. Girolami, Emissions stimulated by high latitude ELF wave injections, invited paper to be presented at the 1981 URSI Meeting, Washington, D.C., 10-19 August 1981.

APPENDIX A

IMPEDANCE AND RADIATION

RESISTANCE OF THE ANDOYA,

NORWAY 60 kV TRANSMISSION LINE

(H. M. Dazey and H. C. Koons)

1.0 INTRODUCTION

Antennas used to radiate power at very low frequencies and extremely low frequencies (VLF, ELF) must have large dimensions (effective heights of hundreds of meters) in order to achieve usable efficiencies. Balloons have been used to support VLF antennas,[1] wires have been suspended between mountains[2] and antennas have been strung over glacial ice[3] in order to achieve the dimensions desired.

Scientists interested in the European Space Agency satellite GEOS, have expressed an interest in transmitting ELF signals to GEOS using 21.3-km long power line as the antenna. The line normally carries 60 kV of three-phase power on the Island of Andøya near the town of Andenes, Norway. The Transportable Very-Low-Frequency (TVLF) System, presently at The Aerospace Corporation, can generate up to 100 kW and would be useful for coordinated ELF/VLF experiments with GEOS, SCATHA, ISEE and other satellites.

Prof. M. Garnier, National d'Etudies des Telecommunication, France, has measured the impedance of the Andøya line at a number of discrete frequencies with both an open and short circuit termination in order to determine the tuning circuit required to operate a 1 kW transmitter in conjunction with the GEOS program. Tuning circuits become more costly when larger amounts of power are being used. Therefore, Mr. Mitchell Dazey of The Aerospace Corporation performed complementary measurements to those of Prof. Garnier's by using a sweeping analyzer with a tracking oscillator to produce an impedance plot over a wide frequency range. Power line harmonics and VLF stations are identifiable in the impedance sweeps and their effects can be eliminated by inspection.

2.0 DESCRIPTION OF THE LINE AND MEASUREMENT PROCEDURES

The Andøya 60-kV transmision line is 21.3 km long, and is strung over somewhat rugged hilly terrain between Andenes and Dverberg. At the time of the measurement, April 29, 1977, there was 2 to 5 feet of wet snow over most of the route.

The line consists of three Fe–Al conductors of 70 mm^2 area spaced two meters apart about 7.8 meters above the ground. The value used for the diameter is 0.00687 m. The three conductors were connected in parallel for the tests with the earth as the return conductor.

Provisions were made by the local power company to allow access to the line at the Andenes end, and to provide an open or short circuit termination upon request at the Dverberg end. The power company allows use of the line when the main demand load can be carried by an older 22-kV line, typically between 12 midnight and 6 a.m. local time.

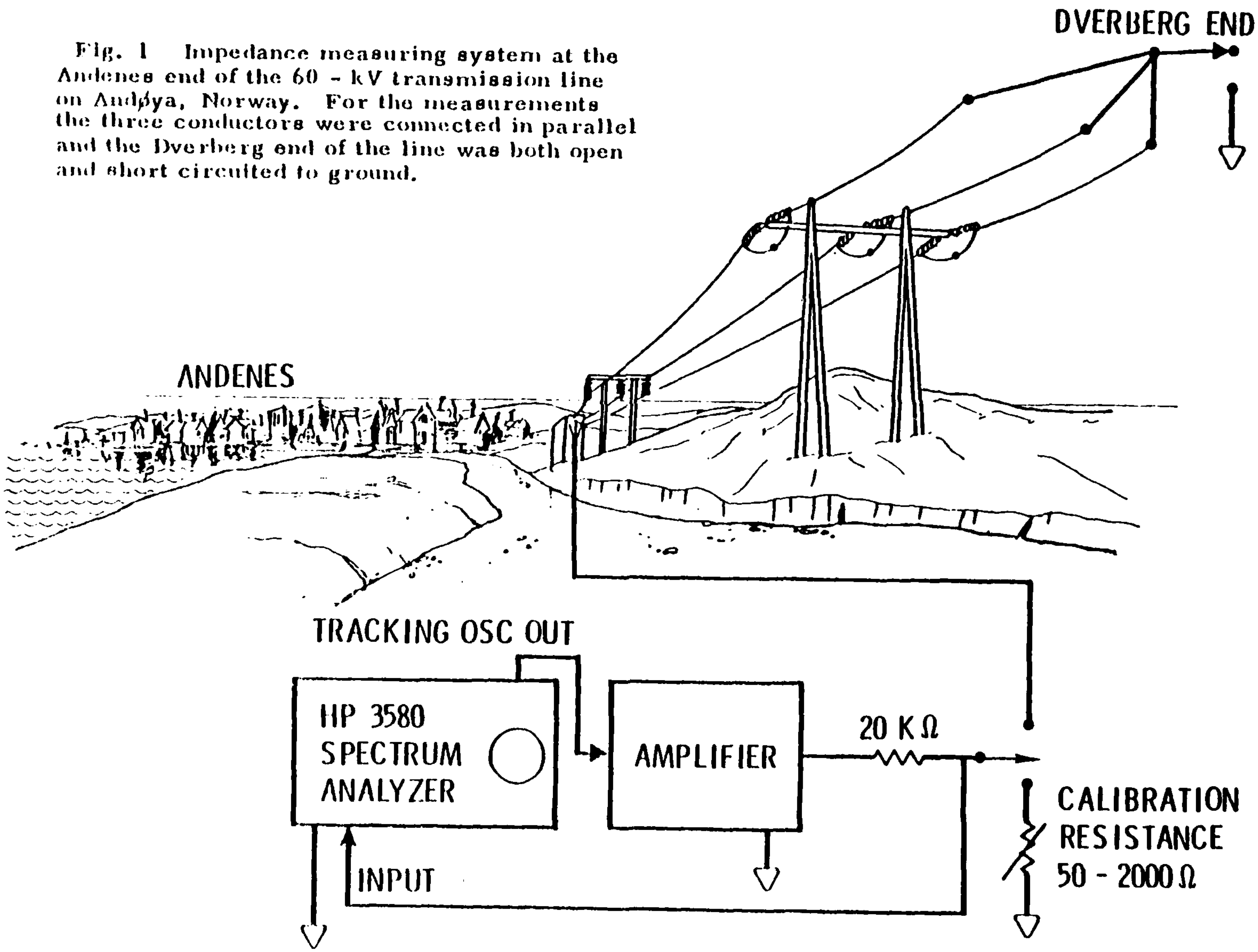
Impedance measurements were made with a Hewlett Packard Model 3580 Spectrum Analyzer. A diagram of the measurement system is shown in Fig. 1. The tracking oscillator output of the spectrum analyzer was amplified and connected to the transmission line and the Y-axis input to the analyzer through a 20,000 ohm resistor. An X-Y recorder was not available, so the traces were photographed with a Polaroid camera. Amplitude calibrations were obtained by substituting a decade resistance box for the transmission line and plotting known impedance levels.

3.0 DATA REDUCTION

The basic data obtained in the measurements was the open and short circuit impedance (Z_{oc}, Z_{sc}) versus frequency over the range from 1 to 20 kHz. Polaroid pictures of the spectrum analyzer traces were enlarged 2.5 times. Since the analyzer reticle is not lighted, a grid was added at the time of making the copies. The analysis was based on measurements of careful tracings of Z_{oc} and Z_{sc} such as those in Figs. 2a and 2b.

In general, the impedance curves indicate a well behaved low-loss transmission line. The power line harmonics cause the impedance value to depart from expected values below one kilohertz and thus may be eliminated by inspection. The VLF stations appear as narrow 'pips' at the higher frequencies and a smooth curve is used to connect the impedance plots when tracings are made. Two data sets were taken. The first sweeping 0-20 kHz and the second sweeping 0-10 kHz.

Fig. 1 Impedance measuring system at the Andenes end of the 60 - kV transmission line on Andøya, Norway. For the measurements the three conductors were connected in parallel and the Dverberg end of the line was both open and short circuited to ground.



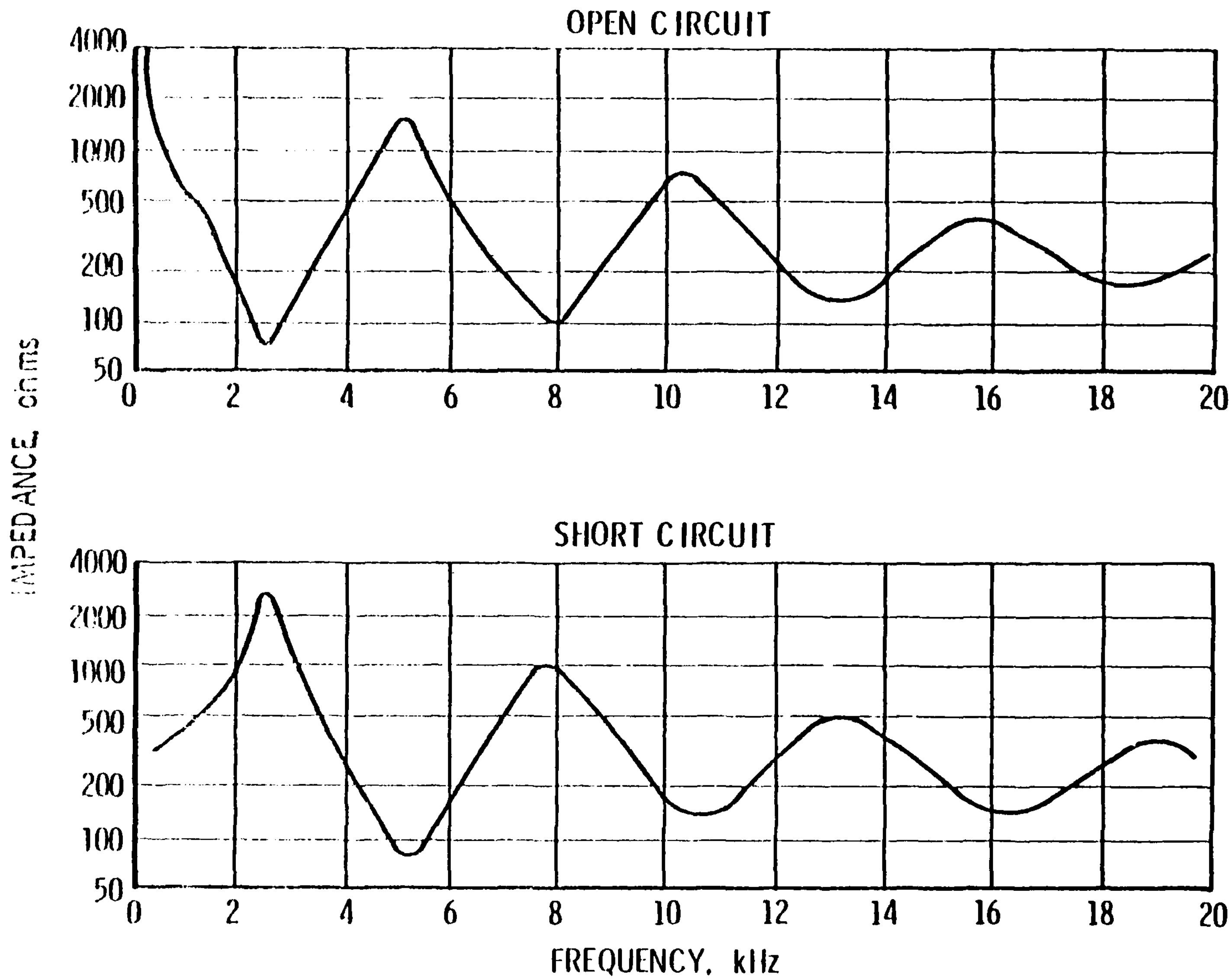


Fig. 2a Open circuit impedance Z_{oc} and short circuit impedance Z_{sc} of the Andøya line as a function of frequency. First data set covering 0 - [illegible] kHz.

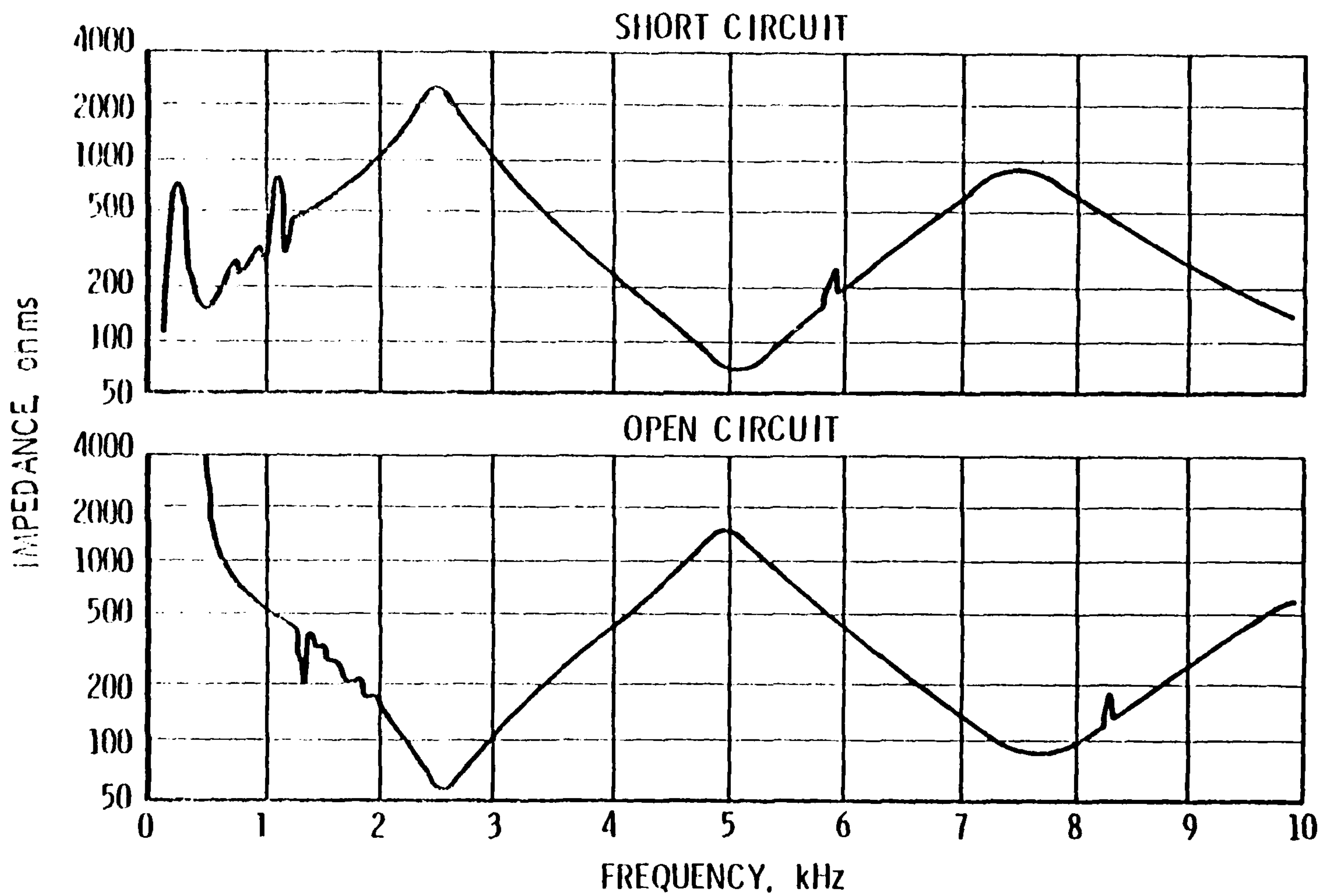


Fig. 2b Short circuit impedance Z_{sc} and open circuit impedance Z_{oc} of the Andøya line as a function of frequency. Second data set covering 0 - 10 kHz.

Figure 3 is a plot of the magnitude (modulus) of the characteristic impedance Z_o as a function of frequency for the two data sets obtained from the following expression:

$$Z_o = \sqrt{Z_{oc} \times Z_{sc}} \tag{1}$$

The velocity of propagation v_p of a transmission line may be determined from:

$$v_p = 4 f_n \ell / n \text{ meters/second} \tag{2}$$

where f_1 = first resonant frequency (quarter wave, n = 1)
f_n = the nth resonant frequency
ℓ = physical length of line (21,300 m)

The effective dielectric constant may be determined from

$$\frac{v_p}{c} = \frac{1}{\sqrt{\epsilon}} \tag{3}$$

where $c = 3 \times 10^8$ m/sec. Figure 4 is a plot of v_p/c as a function of frequency. v_p/c is typically 0.74 giving $\epsilon = 1.82$.

Figure 5 is a plot of the inductance and capacitance per meter of line as a function of frequency as obtained from the following expressions:

$$L = Z_o/v_p \quad \text{henrys/meter} \tag{4}$$

$$C = 1/(Z_o v_p) \quad \text{farads/meter} \tag{5}$$

where Z_o was taken from Fig. 3 (triangles) and v_p was taken from Fig. 4.

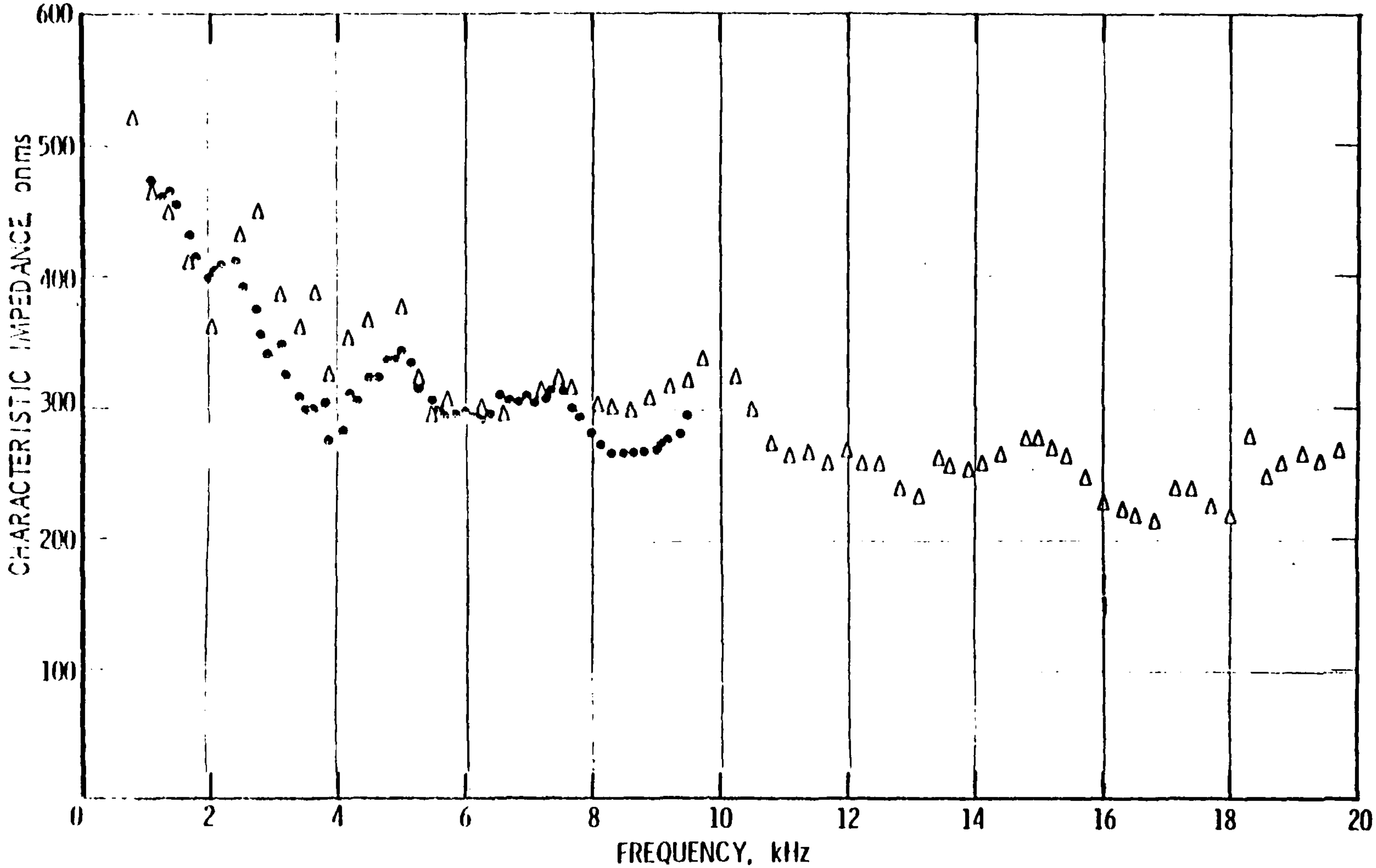


Fig. 3 Characteristic impedance $Z_o = (Z_{sc} Z_{oc})^{1/2}$ of the Andøya line as a function of frequency. Triangles computed using the first data set, Fig. 2a. Circles computed using second data set, Fig. 2b.

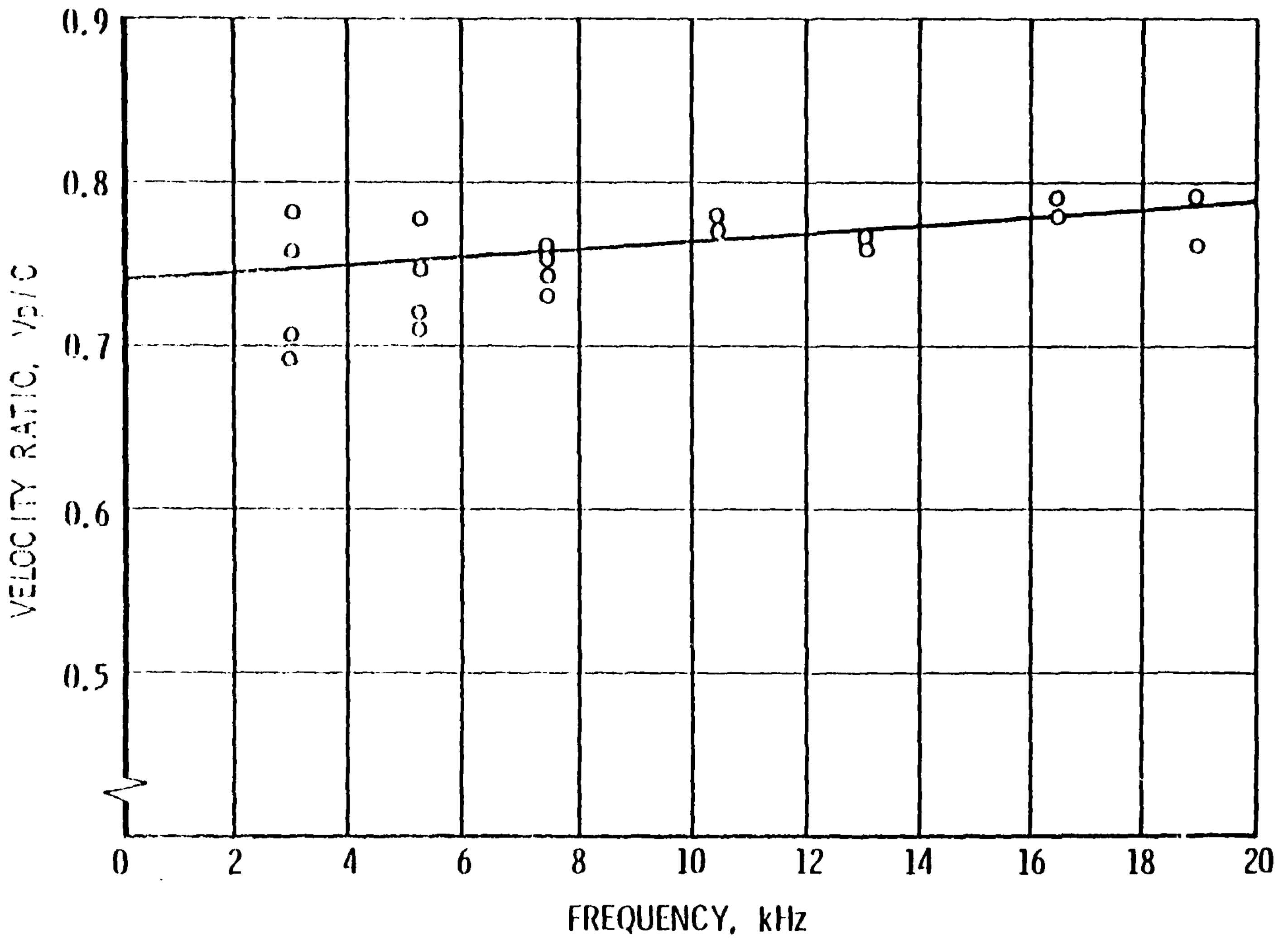


Fig. 4 Ratio of the signal propagation velocity to the speed of light as a function of frequency. The values were determined at the line resonances and antiresonances.

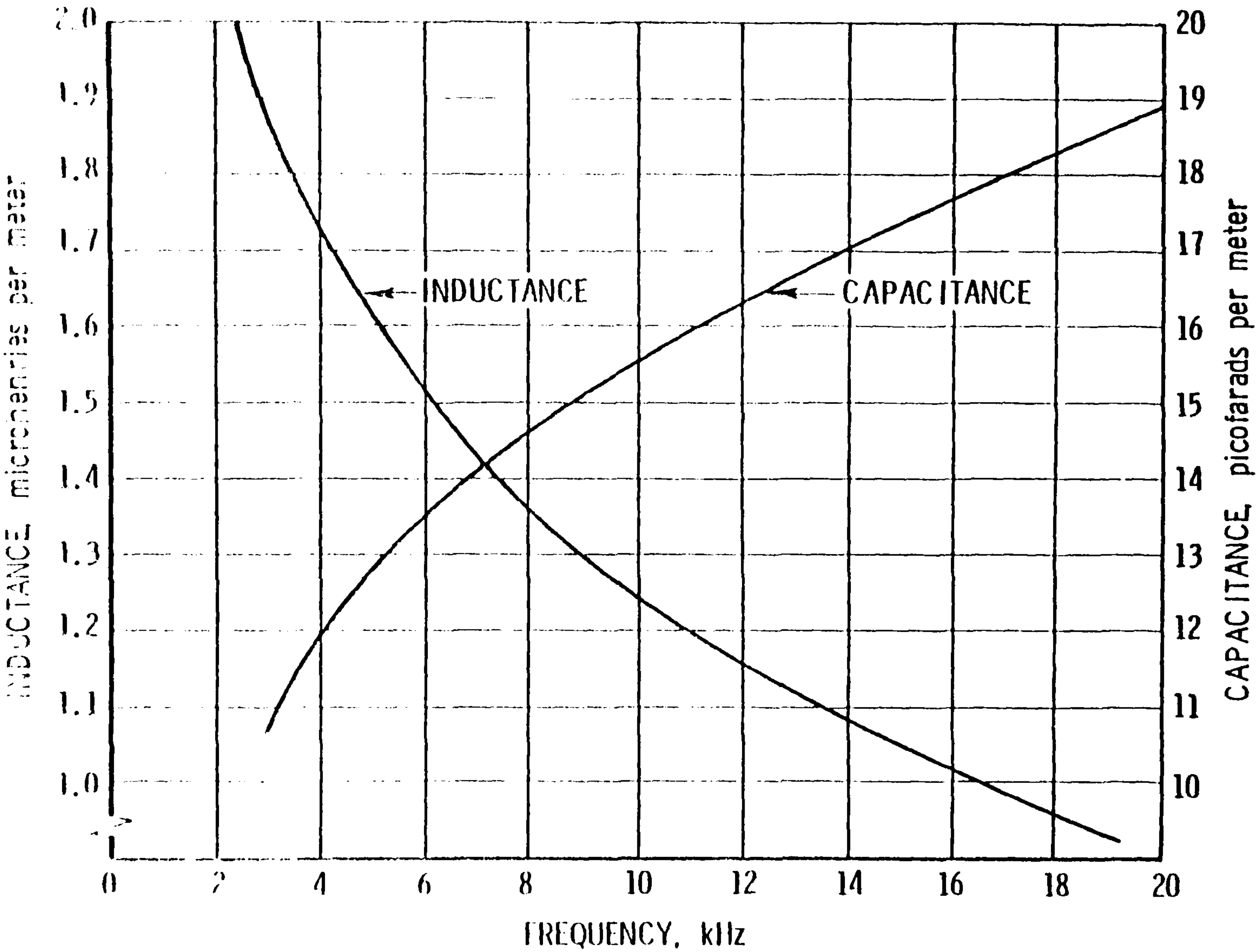


Fig. 5 Line inductance and capacitance per unit length.

The resistance per meter as a function of frequency is shown in Fig. 6. Values were determined from the magnetitudes Z_i of the resonances and anti-resonances which appear in Fig. 2.

For anti-resonance (low impedance)

$$R = 2Z_i/21{,}300 \quad \text{ohms/meter} \tag{6}$$

For resonance (high impedance)

$$R = 2Z_o^2/21{,}300Z_i \quad \text{ohms/meter} \tag{7}$$

Nunn[4] has shown (p. 29) that the resistance of the ground return is independent of the ground conductivity. His expressions, neglecting wire resistance, is:

$$R = \pi^2 f \times 10^{-7} \quad \text{ohms/meter} \tag{8}$$

The values from this expression are also plotted in Fig. 6.

4.0 ANALYSIS

Two important parameters of a transmission line used for an ELF/VLF antenna are:

1. The complex input impedance at the operating frequencies.
2. The effective height associated with the loop formed by the conductors and the earth-return current path.

Knowledge of the complex impedance allows one to design tuning elements, if necessary, and determine the current that will be supplied by a power source of known internal impedance. Knowledge of the effective height and area of the antenna loop

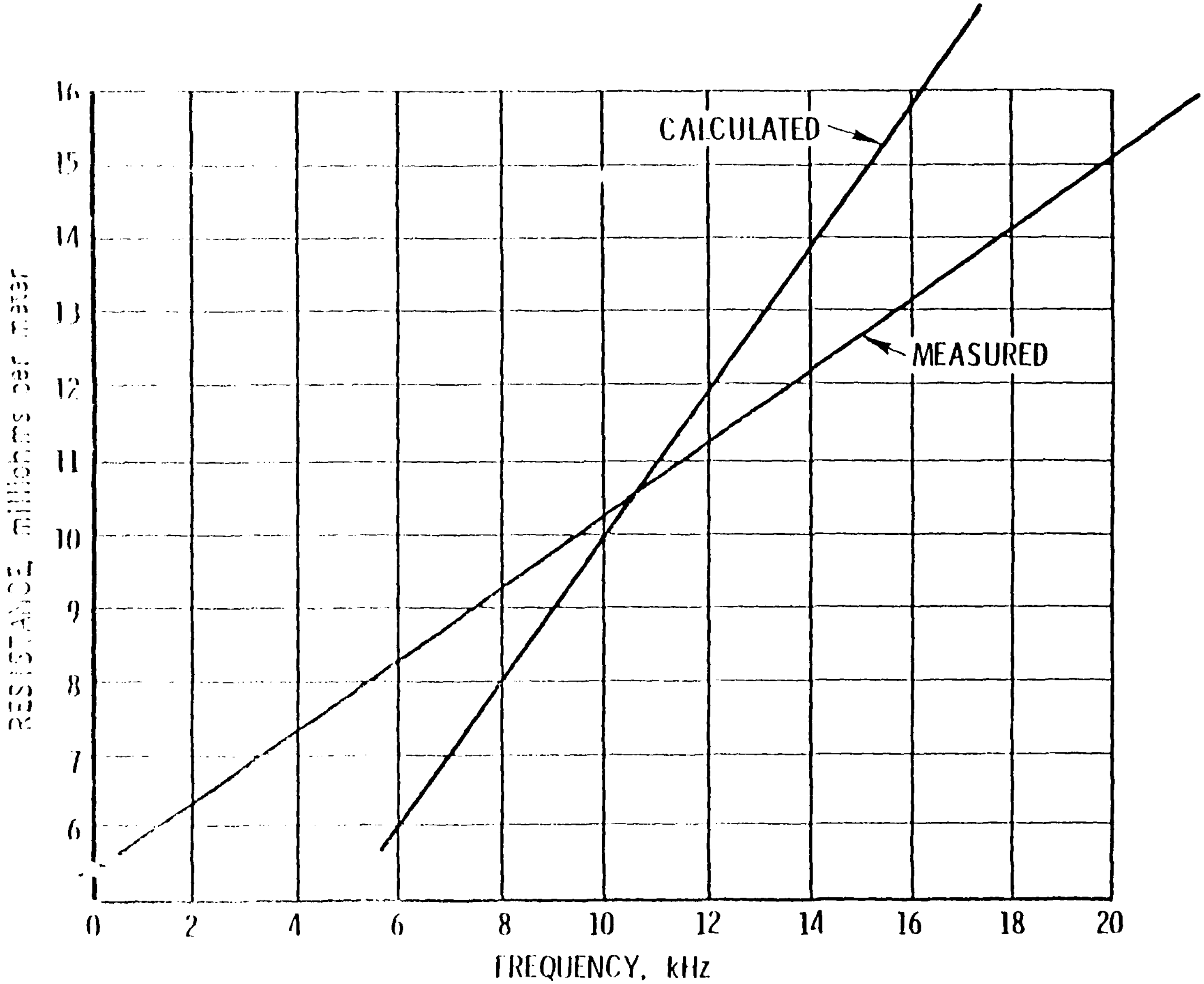


Fig. 6 Line resistance per unit length. The curved marked 'expected' was calculated using the theory presented by Hoon.[1] The curved marked 'observed' is based upon the impedance measurements described in this report.

enables one to determine antenna efficiency and radiated power as a function of the input power.

Ramo and Whinnery[5] provide a convenient table of transmission line relationships, including the general line, a low-loss line and an ideal or lossless line. The "constants" of a transmission line are: resistance/meter, R; inductance/meter, L; conductance/meter, G; and capacitance/meter, C.

A number of analytical compromises will be made for simplicity, recognizing that one could insert expressions for the general line if a refinement of the results is desirable. If we set G = O, we imply that the insulators are lossless and the dielectric losses in the earth are negligible. At times we will let $R/\omega L = 0$, although one can determine from Figs. 5 and 6 that it varies from 0.23 at 2 kHz to 0.11 at 20 kHz. If $R/\omega L$ is not zero the propagation constant is changed slightly, and the characteristic impedance has a small imaginary term.[5]

The impedance measurement system shown in Fig. 1 provides the magnitude of the input impedance for the shorted and open line as a function of frequency, Fig. 2. The real and imaginary parts of Z_{oc} and Z_{sc} must be determined in order to design tuning networks and estimate efficiency. Ramo and Whinnery[5] provide expressions for the input impedances. A typical expression is as follows:

$$Z_{sc} = Z_o \left(\frac{\alpha \ell \cos \beta \ell + j \sin \beta \ell}{\cos \beta \ell + j \alpha \ell \sin \beta \ell} \right) \tag{9}$$

where

$$\alpha = \frac{R}{2Z_o}, \quad \beta = \frac{2\pi f}{v_p}, \quad \ell = 21{,}300 \text{ m}$$

The real and imaginary parts of Equation (9) may be separated algebraically for computation. The Appendix contains the expression for Z_{oc} and the separated equivalent for Z_{sc} and Z_{oc}. Empirical expressions which represent the observed variation of the velocity of propagation and resistance with frequency are also shown in the Appendix.

Table I is a list of measured input impedances of the Andøya line over the frequency range of interest to the GEOS program, with Prof. Garnier's results included. Also shown are the equivalent inductance or capacitance for a simple series circuit. The results obtained by Prof. Garnier using bridge techniques were converted algebraically using expressions presented in the Appendix. While the agreement between the two methods is not startling, it should be considered reasonable considering the handicap of considerable line harmonics existing on the transmission line, the unavailabity of an X-Y recorder, and an element of fatigue associated with travel and the early morning hours during which the measurements were made.

The determination of the effective height associated with the loop formed by the conductors and the earth return is less straightforward than the detemination of the input impedance. Michael Schulz (private communication) has patiently determined the characteristic impedance of a three-wire line above an infinitely conducting ground plane:

$$Z_o = 138\, \epsilon^{-1/2} \left[\!\left[\log(4h/d) \log\left\{(4h/d)\left[1+(h/D)^2\right]^{1/2}\right\} - 2\left\{\log\left[1+(2h/D)^2\right]^{1/2}\right\}^2 \right]\!\right] \div \log\left\{(4h/d)^3\left[1+(2h/D)^2\right]^{-2}\left[1+(h/D)^2\right]^{1/2}\right\} \qquad (10)$$

where:

h	=	height above ground plane
d	=	wire diameter 0.00687 m
D	=	wire spacing = 2 m
ϵ	=	dielectric constant of space surrounding the wires

For the case of a transmission line above a conducting earth, some simplifying assumptions must be made:

TABLE I
RESISTIVE AND REACTIVE IMPEDANCES OF THE ANDOYA
60 kV TRANSMISSION LINE AS CALCULATED FROM
0-20 kHz POLAROID FILMS MADE APRIL 1977

	SHORT CIRCUIT TERMINATION				OPEN CIRCUIT TERMINATION			
Frequency	Resistive Impedance ohms	Reactive Impedance ohms	L or C Equiv.	L or C To Tune	Resistive Impedance ohms	Reactive Impedance ohms	L or C Equiv.	L or C To Tune
1000 Hz	91(38)	307(195)	0.049 H	0.52 μF	186 (186)	-633(-1347)	0.25 μF	0.040 H
1100	100	344			163	-577		
1200	110	383			143	-512		
1300	125	426			127	-434		
1400	142	473			115	-382		
1500	163	525	0.056 H	0.20 μF	98(14)	-315(-199)	0.34 μF	0.033 H
1600	201	596			96	-286		
1700	228	647			90	-257		
1800	227	718			85	-222		
1900	344	803			81	-189		
2000	439(320)	896(817)	0.071 H	0.089μF	78(23)	-159(-74.6)	0.50 μF	0.012 H
2100	577	1003			75	-131		
2200	782	1111			73	-104		
2300	1088	1187			72	- 78		
2400	1521	1148			71	- 54		
2500	2025	841	0.075 H	0.053μF	71	- 29	2.2 μF	0.002 H
2600	2287	181			71	- 5		
2700	2090	-507			72	17		
2800	1628	-889			73	39		
2900	1190	-984			74	62		
3000	868(375)	-940(-895)			77	83		
4000	142(75)	-310(-293)			158	346		

Values in parenthesis were obtained from Professor Garnier's bridge measurements of resistance, inductance and capacity in April 1977. His values were converted to impedances for purposes of comparisons.

a. There is an effective dielectric constant which may be determined from the velocity of propogation.

b. The skin depth δ in earth is much larger than the 7.8 meter height of the suspension towers.

c. The effective distance h to an equivalent ground plane in a conducting earth is given by:

$$h = \frac{\delta}{\sqrt{2}} \tag{11}$$

The assumption is based on Ref. 4 page 21, where Nunn states that the inductance for a single-wire line above earth is:

$$L = \frac{\mu_o}{2\pi} \ln\left(\frac{\delta\sqrt{2}}{a}\right) \quad H/m \tag{12}$$

where:

μ_o = $4\pi \times 10^{-7}$ henrys/meter

δ = skin depth associated with earth conductivity

a = wire radius

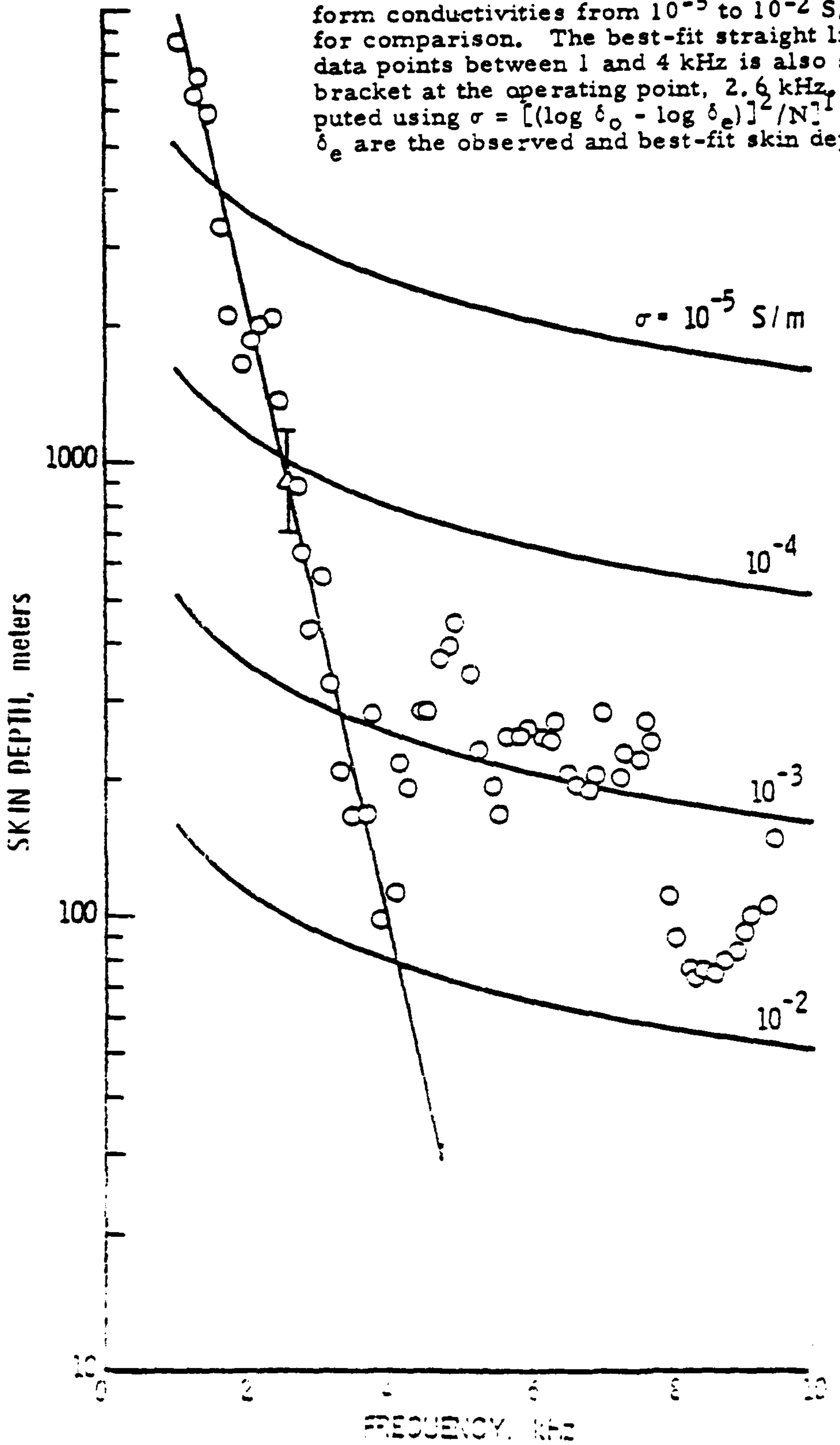
This may be compared to the classic expression for a wire a distance h above a conducting plane:

$$L = \frac{\mu_o}{2\pi} \ln\left(\frac{2h}{a}\right) \quad H/m \tag{13}$$

By using the data from Fig. 3 (circles), $1/\sqrt{\epsilon} = .74$ obtained from Fig. 4, and Equations (10) and (11) we calculate the skin depth in the earth as a function of frequency. This result is shown in Fig. 7.

The power radiated P_r is a function of the power available P_a, the generator impedance, the load impedance and the effective loop area. The TVLF System has a 300-ohm output and a matching transformer with taps from a few ohms to 43 ohms. If the

Fig. 7 The effective skin depth of the Andøya transmission line (circles). The skin depth for uniform conductivities from 10^{-5} to 10^{-2} S/m are shown for comparison. The best-fit straight line for the data points between 1 and 4 kHz is also shown. The bracket at the operating point, 2.6 kHz, was computed using $\sigma = [(\log \delta_o - \log \delta_e)]^2/N]^{1/2}$ where δ_o and δ_e are the observed and best-fit skin depths respectively.



load impedance is higher than the generator impedance the available power will be voltage limited. Conversely if the load impedance is lower than the generator impedance the power will be current limited. The voltage and current limits for a generator with internal impedance Z_g are given by:

$$V_{max} = \sqrt{P_a Z_g} \text{ and } I_{max} = \sqrt{P_a / Z_g} \qquad (14)$$

The relationship for power radiated is less straightforward. For simplicity, radiation resistance R_r is used and is related to the input current I, and the power radiated by:

$$P_r = I^2 R_r \qquad (15)$$

An expression for the radiation resistance for long antennas with earth return, which assumes that the antenna couples into the earth ionosphere waveguide rather than the energy spreading in the classic inverse square manner, is[6]

$$R_r = \frac{(2\pi f)^2 \ell^2}{8 c^2 \sigma h_i} \qquad (17)$$

Using

$$\frac{f}{c} = \frac{1}{\lambda}; \quad \frac{1}{\sigma} = \delta^2 \pi f \mu_o; \text{ and } \sqrt{\frac{\mu_o}{\epsilon_o}} = 377 \text{ ohms}$$

This may be written

$$R_r = \frac{\pi^3 \times 377\ \delta^2 \ell^2}{h_i \lambda^3 \times 2} \text{ ohms} \qquad (18)$$

where

h_i = the ionospheric height, typically 80,000 meters.

δ = skin depth (meters) of the earth below the line (assumed to be much larger than the height of the line above the earth).

c = 3×10^8 meter/sec.

σ = earth conductivity in siemens/meter

λ = wavelength in meters

ℓ = length of line, 21,300 meters

μ_o = $4\pi \times 10^{-7}$ henry/meter

ϵ_o = $(1/36\pi) \times 10^{-9}$ farads/meter

Equation (17) assumes σ is uniform with depth and over the length of the line.

We note that the radiation resistance goes inversely as the cube of wavelength, rather than the fourth power as in classical expressions.

5.0 RADIATED POWER

We will now calculate the radiation expected using the previously determined parameters of the Andøya 60-kV line. The reactive impedance of a transmission line is zero at the resonances. If we select the lowest resonant frequency from Fig. 2 no tuning elements will be necessary. The open-c it line is resonant at 2.6 kHz with an input impedance of 71 ohms. Assuming the power available from the TVLF system is 100 kW, we may check our two most logical impedances. Using Equation (14), we have:

Generator Impedance	Limit Mode	Value	Input Current for 71 ohm load
300 ohms	Current	18.25 A	18.25 A
43 ohms	Voltage	2,024 V	29.2 A

We select the 43 ohm output impedance and assume we can supply an input current of 29 amperes. We will ignore the fact that we could buy or fabricate a transformer which would give a perfect match and an increased current.

From the best-fit straight line to the data between 1 and 4 kHz in Fig. 7 we find the skin depth at 2.6 kHz is 910 meters. The radiation resistance from Equation (18) and the power radiated from Equation (15) are then:

$$R_r = .018 \text{ ohms}$$

$$P_r = 15.1 \text{ watts}$$

6.0 ACCURACY

The original data were obtained by photographing the spectrum analyzer display with a hand-held Polaroid camera. The basic data had to be aligned by hand with the frequency grid which leads to inaccuracies which would not have existed using an X-Y recorder. Certain physical factors can introduce errors, e.g. the inductance in the short-circuit termination, and the non-uniform earth conductivity over the length of the line. For simplicity it was assumed that the earth conductivity was uniform with depth and over the length of the line.

Within the limitations of the available data an estimate of the error can be made from the standard deviation of the data between 1 and 4 kHz in Fig. 7. The results are:

$$\delta = 910 {}^{+282}_{-216} \text{ meters}$$

$$R_r = .018 {}^{+.013}_{-.007} \text{ ohms}$$

$$P_r = 15.1 {}^{+11}_{-6.5} \text{ watts}$$

The 20-kHz data set (triangles) in Fig. 4 shows a systematically higher characteristic impedance than the 10-kHz data set (circles) used to obtain the results reported here. The higher characteristic impedance would predict a larger skin depth and larger radiated power than the data set analyzed in this report.

Nunn[4] has performed detailed theoretical calculations on the propagation of ELF pulses from a ground-based transmitter to the GEOS satellite. He concludes that a 45 kW transmitter driving an antenna over a ground with $\sigma = 10^{-4}$ S/m will produce a signal at GEOS with a signal-to-noise ratio of 7.5 in the absence of magnetospheric amplification. He assumes that a duct is required to guide the signal to the equator.

The Aerospace TVLF transmitter is capable of delivering 100 kW to the Andøya antenna. If we derate the transmitter to 80 kW and use $\sigma = 1.2 \times 10^{-4}$ S/m at 2.6 kHz as shown on Fig. 7 the signal-to-noise ratio at GEOS using the TVLF transmitter will be:

$$S/N = 7.5 \left(\frac{80}{45}\right)^{1/2} \left(\frac{10^{-4}}{1.2\times10^{-4}}\right)^{1/2} = 9.13 \qquad (=19\text{dB})$$

7.0 CONCLUSIONS

The swept frequency technique, when used with a narrow-band analyzer, allows one to measure the impedance of power transmission lines over a wide frequency range. Impedance data masked by power line harmonics are easily eliminated by inspection. The measuring technique, applied to the Andøya, Norway 60-kV power line, indicates the conductivity of the earth under the power line is not uniform. Using a frequency range that covers several resonances we have determined the inductance, capacitance and resistance per unit length, as well as measure the variation of the velocity of propagation of the line.

Using simplifying assumptions we have calculated the power which will be radiated if the line is excited by a high power VLF amplifier. Derating the Aerospace TVLF transmitter to 80 kW we obtain a signal-to-noise ratio at 2.6 kHz of 19 dB at GEOS based upon Nunn's[4] theoretical analysis of ducted propagation from a high-latitude transmitter.

APPENDIX

This appendix is provided for the convenience of those who may wish to make a detailed check of the results in the attached report, or possibly make their own analysis of a similar transmission line.

Reference 5 contains the input impedance relationships for no loss, low loss, and general transmission lines. The low loss relationships were used in this report. For a short circuited line:

$$Z_{sc} = Z_o \left[\frac{\alpha \ell \text{ Cos } \beta \ell + j \text{ Sin } \beta \ell}{\text{Cos } \beta \ell + j \alpha \ell \text{ Sin } \beta \ell} \right]$$

Separating real and imaginary parts:

$$Z_{sc} = \frac{Z_o}{\text{Cos}^2 \beta \ell + (\alpha \ell)^2 \text{ Sin}^2 \beta \ell} \left\{ \alpha \ell - j[(\alpha \ell)^2 - 1] \text{Sin } \beta \ell \text{ Cos } \beta \ell \right\}$$

For an open circuit Line:

$$Z_{oc} = Z_o \frac{\text{Cos } \beta \ell + j \alpha \ell \text{ Sin } \beta \ell}{\alpha \ell \text{ Cos } \beta \ell + j \text{ Sin } \beta \ell}$$

Separating real and imaginary parts:

$$Z_{ioc} = \frac{Z_o}{(\alpha \ell)^2 \text{ Cos}^2 \beta \ell + \text{Sin}^2 \beta \ell} \left\{ \alpha \ell + j[(\alpha \ell)^2 - 1] \text{Sin } \beta \ell \text{ Cos } \beta \ell \right\}$$

where

$$\alpha = \frac{R}{2Z_o}, \quad \beta = \frac{2\pi f}{v_p}, \quad \ell = 21,300 \text{ m}$$

R = ohms/meter of transmission line

Z_o = characteristic impedance $-\sqrt{Z_{oc} \times Z_{sc}}$

The quantities v_p and R are approximated as straight lines as a function of frequency in Figures 4 and 5. For the purposes of computations, the quantities were represented by the following empirical expressions:

$$v_p = 3 \times 10^8 \, (2 \times 10^{-6} f + 0.74) \text{ m/sec}$$

$$R = (4.8 \times 10^{-7} f + 5.41 \times 10^{-3}) \, \Omega/\text{m}$$

where f = frequency in Hz

The bridge measurements made by Prof. Garnier on April 28, 1977 were described in a note which was sent to us. The measured values are shown below together with impedances calculated from those values. Some measurements were termed "Maxwell Bridge Measurements" which assume the components (a resistor and an inductance) are in series. Other measurements were termed "Sauty Bridge Measurements" which assumes the components (a resistor and a capacitor) are in parallel.

In addition, Prof. Garnier resonated the line with several values of capacitance, which gives values of reactive impedance, from which inductance may be determined.

The algebraic equivalents which were used to convert Prof. Garnier's measurements are shown below:

$$\text{Reactive impedance,}\quad X_l = j\omega L$$

$$X_c = \frac{1}{j\omega C}$$

$$\omega = 2\pi f \text{ radians/sec}$$

The input impedance Z_i of a circuit with resistance R_p, in parallel with a capacitor C_p, at an angular frequency ω, is given by:

$$Z_i = R_p \left(\frac{1 - j(\omega C_p R_p)}{1 + (\omega C_p R_p)^2} \right)$$

The values of the series resistance R_s, and series capacitance C_s, are:

$$R_s = \frac{R_p}{1 + (\omega C_p R_p)^2} \text{ ohms}$$

$$C_s = C_p \left\{ 1 + \frac{1}{(\omega C_p R_p)^2} \right\} \text{farads}$$

Table II contains the values included in Prof. Garnier's notes with the values of impedances and equivalent series components as determined from the expressions above.

TABLE II

Prof. Garnier's bridge measurements of the Andoya 60 kV Transmission Line made on April 28, 1977 with equivalent circuit values

Line Termination	Freq. (hertz)	Prof. Garnier's Measurements		Equivalent Series Values		Impedance	
		Resistance	L or C	R_s	L_s or C_s	React.	Total
MAXWELL BRIDGE							
Short circuit	1000	38Ω	.031 H	38Ω	.031 H	195Ω	198Ω
	2000	320Ω	.065 H	320Ω	.065 H	817Ω	877Ω
SAUTY BRIDGE							
Short circuit	3000	2510 Ω	.0504μf	375Ω	.059 μf	895Ω	970Ω
	4000	1220 Ω	.127 μf	75.5Ω	.136 μf	293Ω	303Ω
Open circuit	1000	10,100Ω	.116 μf	183Ω	.118μf	1347Ω	1359Ω
	1500	2,700Ω	.53 μf	15Ω	.53 μf	199Ω	199Ω
	2000	260Ω	.97 μf	23Ω	1.07μf	74.6Ω	78Ω
RESONANCE MEASUREMENTS							
			C to Resonate		Equivalent Inductance		
Short circuit	1000		.71 μf		.0357 H	224Ω	
	1500		.2 μf		.0563 H	531Ω	
	1800		.1 μf		.078 H	882Ω	
	2000		.07 μf		.0905 H	1137Ω	

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APPENDIX B

THE SORTLAND NORWAY TRANSMISSION LINE VLF TEST SEPTEMBER - OCTOBER 1978

(M. H. Dazey)

1.0 INTRODUCTION

Very low frequency (VLF) transmissions from the surface of the earth to the European Space Agency satellite GEOS and the U. S. Air Force satellite SCATHA can be useful in studying wave-particle interactions in the outer magnetosphere. The longitudinal positioning of GEOS and the expected orbit of SCATHA makes it desirable to make the VLF transmissions from Scandinavia.

An informal cooperative program was arranged by Aerospace personnel with the European Space Agency Personnel, and the Royal Norwegian Council for Scientific and Industrial Research (NTNF), Space Activity Division. The Aerospace Corporation would supply the 100 kW Transportable Very Low Frequency (TVLF) System with funding by the National Science Foundation, while the Norwegians would supply a suitable antenna and make local arrangements.

VLF transmitting antennas typically have required either large, expensive, permanent structures, or temporary systems such as a tethered balloon or an airborne long wire. GEOS scientists have arranged for the use of a long electrical power transmission line as an antenna, thereby eliminating installation costs and making operation possible in weather conditions that would destroy a balloon supported antenna.

A 22 km, 60 kilovolt line, referred herein as the Andoya line, was made available at Andenes, Norway. Professor Garnier, Centre National d'Etudes des Telecommunications, University of Paris, France, measured the impedance at a number of discrete frequencies with open and short circuit terminations in order to determine the tuning circuit required to operate the line with a French 1 kW transmitter in conjunction with the GEOS satellite.

The 100 kW TVLF system requires a more costly tuning system than the 1 kW transmitter, so it was decided to complement Professor Garnier's measurements by using a sweeping oscillator and tracking oscillator to produce an impedance plot over a wide frequency range. The measurements were completed in June 1977; the expected radiated power was calculated and reported in Reference 1.

In March 1978, Professor Garnier and his people attempted transmissions to GEOS using the 1 kW transmitter and the Andoya line. Use of the 60 kV Andoya line as a VLF antenna requires the electrical load of the town of Andenes to be carried by an older 22 kV line. The tests of March 1978 were made on a very cold night when the electrical load was high and as a consequence the line voltage dropped approximately 20% throughout Andenes and nearby towns. The allowable voltage drop is 10%, and, although

it is not documented, the lowered voltage is believed to have caused some appliance damage in Andenes. No difficulties of any kind were reported related to the local telephone system. The temporary assignment of the 60 kV Andoya line to VLF applications had been arranged on an informal basis with the expectation that local residents would not experience problems. The undesirable consequences caused the NTNF personnel to be extremely reluctant to make further informal agreements to use the Andoya line as a VLF antenna.

In June NTNF personnel informed the Aerospace personnel that the Sortland Line, a line that ran about 34 km between the towns of Strand and Konstadbotn, Norway, was available for use as a VLF antenna. The Sortland line was a "stand-by" line, and was being kept available for use when it was necessary to service an operating line; thus it was not necessary to do any switching or otherwise cause problems with the local electrical distribution network when VLF transmissions were being made.

This report describes the operations with the TVLF system with the Sortland line as an antenna, and the impedance measurements which were obtained in order that the radiated power could be estimated.

2.0 IMPEDANCE MEASUREMENTS

The impedance of the Sortland transmission line operating in the earth return mode was determined by using a tracking oscillator as a constant current source and measuring the voltage across the input of the line with the sweeping analyzer synchronized with the tracking oscillator. Details were described in Reference 1. Tests were made with an open circuit and a short circuit at the Kanstadbotn end.

Analysis of the test results indicated that the Sortland line is not as well behaved electrically (i.e. as a uniform transmission line) as is the Andoya line. The line runs approximately 1000 meters from a fjord for 80% of the distance from Strand to Kanstadbotn. The final 20% is constructed over relatively mountanous terrain. If the final 20% of the line were disconnected and tested separately, it would be expected to resonate in multiples of about 7 kHz. Perturbations in the impedance curves start at approximately that frequency. The simple expression, $Z_o = \sqrt{Z_{sc} \times Z_{oc}}$, from which one can estimate the skin depth, assumes a uniform transmission line.

The experiments planned for GEOS and SCATHA rec e transmissions below 5 kHz. The Sortland line appears to be well behaved bel that frequency. The parameters derived from the experimental data below kHz are shown in Table I.

TABLE I

Free space electrical length (l)	=	34,000 m
Velocity of propagation in the earth return mode	=	2.1×10^{8} m/sec
Inductance per unit length	=	1.57×10^{-6} Hy/m
Capacitance per unit length	=	14.43×10^{-12} F/m
Resistance per unit length	=	8.8×10^{-7} x frequency, ohms/meter
Characteristic impedance (Z_o)	=	$330 \times (1 - .0446j)$ ohms
Propagation Constant (γ)	=	$2\pi f \times 4.77 \times 10^{-9} \times (.0446 + j)$

Figures 1 and 2 show the experimentally observed short and open circuit impedances of the Sortland line and are compared with the predictions of general line equations using the above estimates given and the general transmission line expressions:

$$Z_{sc} = Z_o \text{ Tanh } \gamma l$$

$$Z_{oc} = Z_o \text{ Coth } \gamma l$$

Since Z_o appears to be constant at the lower frequencies it would appear that the effective skin depth of the earth return current is a constant. The Sortland line consists of three conductors with a wire diameter of .0128 m and a spacing of 3m. The line geometry combined with the characteristic impedance of 330 ohms and a velocity of propagation of 2.1×10^8 m/sec (70% of the speed of light) would indicate a skin depth of about 850 meters. The rationale for this type of analysis is presented in Reference 1.

The Andoya Line measurements indicated a significant increase in the characteristic impedance below 4 Khz and the calculated values of characteristic impedance indicated skin depths from 1000 to 10,000 meters. The Sortland line measurements indicate that the skin depth, 850 m, is essentially constant below 4 kHz, and has approximately the same value as the distance to the fjord, 1000 m. This result would seem to indicate that most of the return current travels in the fjord or in the earth between the transmission line and the fjord.

There are two possibilities to consider if the return current indeed is traveling primarily between the transmission line and the fjord. First, the plane of equivalent radiating loop might be horizontal rather than vertical as would be expected with the Andoya line. Second, the transmission line crosses the fjord at about the line midpoint.Therefore the equivalent circuit might be that of two horizontal loops with opposite magnetic moments which would cause partial cancellation of the radiating field. The uncertainties of the loop geometry make it mandatory to obtain far field measurements in order to confidently estimate radiated power.

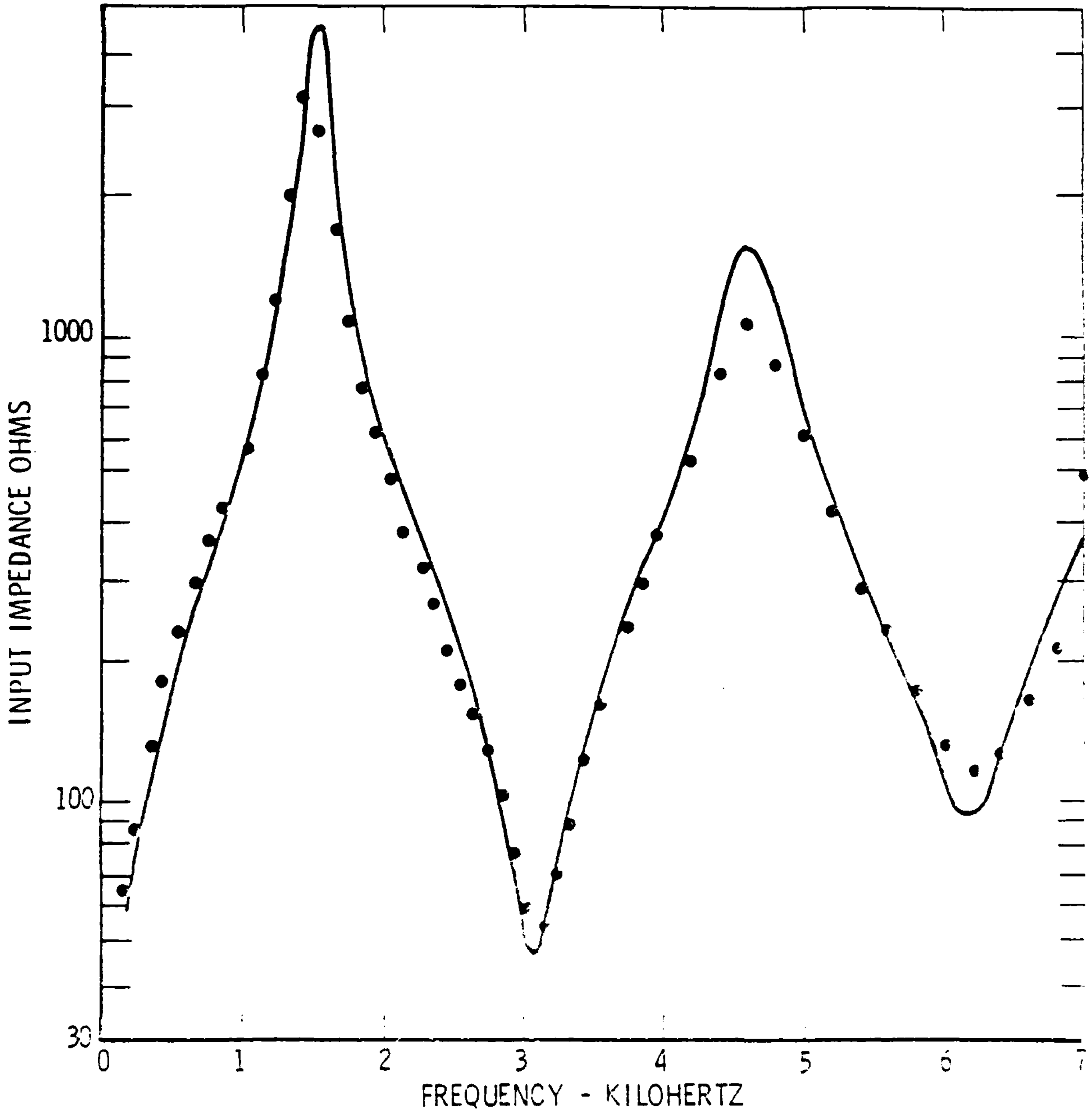

Fig. 1 Input impedance vs frequency. Sortland line with Short Circuit Curve is $Z_{sc} = Z_o \tanh \gamma l$. Z_o, γl, are from Table [illegible] estimates. Data points are values measured September 2[illegible], 19[illegible].

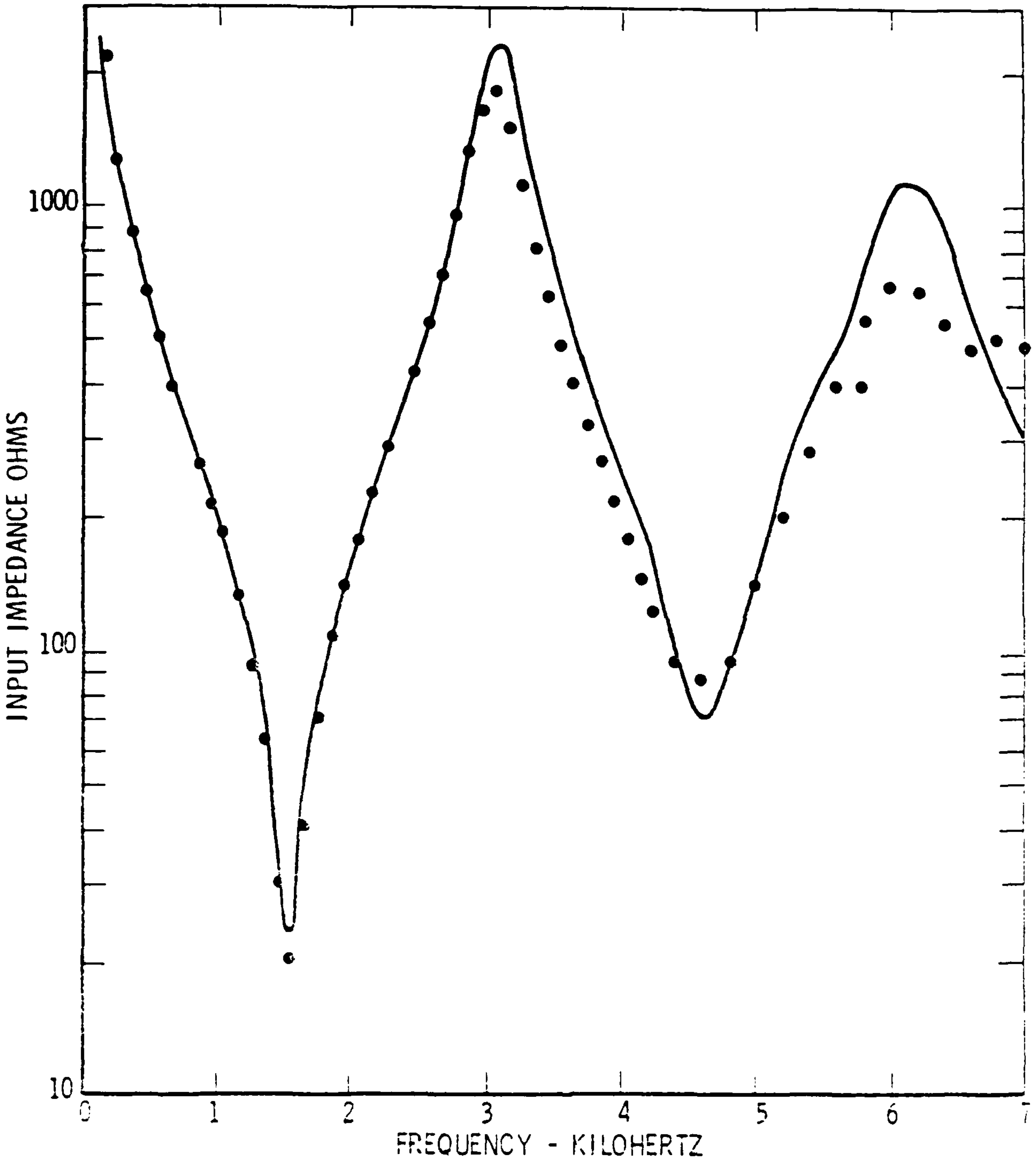

Fig. 2 Input impedance vs frequency. Sortland line with Open Circuit. Curve is $Z_{oc} = Z_o \coth \gamma \ell$ Z_o, γ, ℓ and are from Table 1 estimates. Data points are values measured September 25, 1976.

3.0 POWER TESTS WITH THE SORTLAND TRANSMISSION LINE

The TVLF system demonstrated its capability to supply 106 kW to a 30 ohm resistive load prior to shipment to Norway from El Segundo, California in June 1978.

The two units, the Transmitter trailer and the Engine Generator trailer were towed across the USA to Bayonne, N. J., and shipped to Bremerhaven, Germany. A matching transformer, dummy load and miscellaneous parts were carried on a flatbed truck. From Bremerhaven, the items were shipped to Sortland, Norway, and hauled by truck to Strand. The available maps indicated that the territory between Strand and Konstadbotn contained only a few isolated farms. When the Aerospace personnel arrived at Strand, it was apparent that there were many more farms than indicated on the map, the farms were quite small, and some were located in close proximity to the Strand power house. Further, the power company property at Strand was surprisingly small, and a storage shed prevented the TVLF components from being separated far enough to make the required cable bends between the generators, transmitter, matching transformer and the dummy load.

After consultation with the Norwegian participants it was decided that the houses were too close to the power station to allow operation of the engine generators because of their noise. Therefore it was decided to move the system to the Kanstadbotn end of the Strand transmission line. Some procedural problems were encountered by the Norwegians, because the Kanstadbotn terminal was operated by a different power company and was in a different county. Nevertheless, the TVLF system was moved the 30 km, and placed into operation in three days.

The first low impedance resonance measured at Strand was at 1,550 Hz in the open circuit quarter wave mode, and the measured impedance value was approximately 16 ohms. The operating frequency was chosen to be 1525 Hz which provides good separation from both 50 and 60 Hz harmonics.

Test transmissions with the TVLF system at Kanstadbotn and the 60 KV transmission line as an antenna were begun on 27 September 1978. An antenna current of 40 amperes with an impedance match at 11 ohms was selected as an optimal operating

condition. The maximum antenna current achieved was 60 amperes with a 14 ohm impedance. However, the 60 amp current caused the engine generators to groan, and the plate current to operate close to the allowable limit. The 11 ohm impedance match was somewhat lower than the impedance measurements and theory would have suggested. However, it was the point when the matching elements of the TVLF system indicated the best match. Later events indicated 40 amperes was more than sufficient to create effects which would terminate this first portion of the project prematurely.

Figure 3 is a plot of power output versus frequency which indicates the antenna bandwidth to be about 220 Hz to the 1/2 power points. The 60 amperes current represents about 50 kw into a 14 ohm load, or 40 kw if the load is 11 ohms. The failure to achieve 100 kilowatts is a matter of some concern, since a 100 kw demonstration (into 30 ohms) was accomplished prior to shipment of the TVLF system to Norway. Investigation of the discrepancy must be deferred until the system can be operated at some future date.

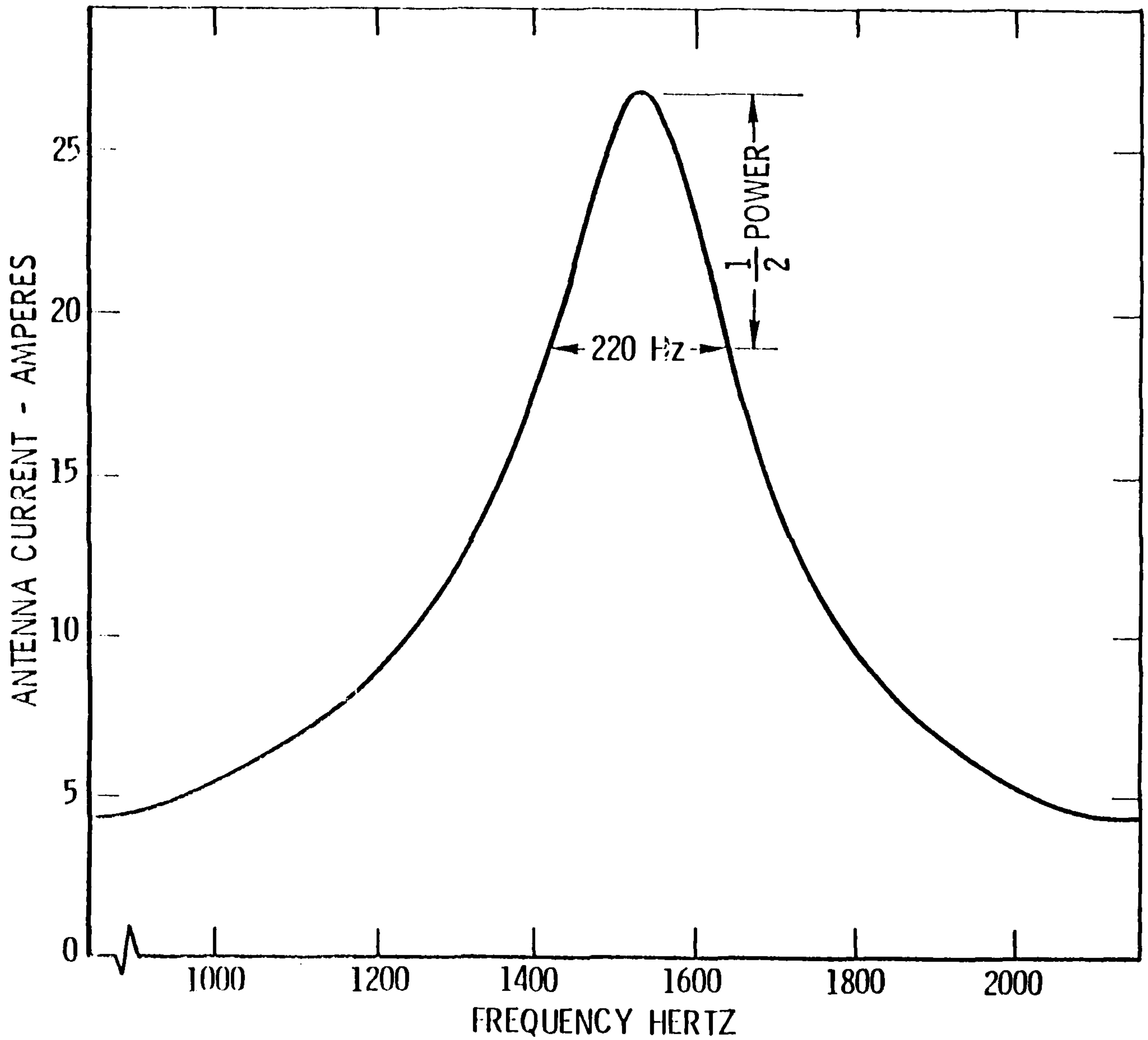

Fig. 3 Antenna Current vs Frequency, Sortland Line driven by TVLF System, Open Circuit Termination.

4.0 FIELD ESTIMATES AND MEASUREMENTS

The radiated power was estimated to be 12 to 18 watts by using the following expressions from Reference 1:

$$R_R = \frac{\pi^3 \times 377 \times (\partial^2 l^2)}{2 h_i (\lambda^3)} \qquad = .0067 \text{ ohms}$$

and $P_R = I^2 R_R = 10.8$ watts

where:

∂	=	skin depth = 850 m
l	=	line length = 34,000 m
h_i	=	ionospheric height = 90,000 m
λ	=	wavelength = 200,000 m
R_R	=	Radiation Resistance, ohms
I	=	antenna current, = 40 amps

The validity of the above expression is subject to question because the wavelength (200 km) is considerably greater than the ionospheric height (90 km).

Field measurements at Andoya indicated a value of 100 μ v/meter, for 40 amperes antenna current, and the distance to the transmitter was 80 km, or .4 wavelength.

If we assume isotropic radiation over 2π steradians, the relationship between field, E, power, P_R and distance, d, is as follows:

$$P_R = \frac{E^2 \times 2\pi d^2}{377} = \frac{(10^{-4})^2 \times 2\pi \times (80{,}000)^2}{377}$$

$$= 1.06 \text{ watts}$$

If we allow for the fact that the 100 μ v/meter measured field includes a component of the near field, the power radiated, assuming an isotropic pattern, would be about 15% less, or 0.91 watts. The orientation of the VLF receiver loop and the antenna pattern of the Sortland line were uncertain. Therefore, there is a possibility that the actual radiated power could be considerably larger than 0.91 watts.

Unsuccessful attempts were made by the University of Sheffield Physics Department to detect the signal at a distance of 1900 km with a receiver sensitivity of 5 microvolts per meter. This sensitivity is equivalent to detection of an isotropic radiator

into 2π steradians with a power of 1.7 watts. However, the relationship between the ionospheric height and the wavelength should greatly increase path attenuation, requiring considerable greater radiated power for detection.

The GEOS satellite acquired data for a considerable length of time while the TVLF system was transmitting. The GEOS VLF receiving system is highly sophisticated and incorporates some on-board processing of received data. The "quick look" data is believed to have a sensitivity of 5 microvolts per meter (private communication, R. L. Dowden, Oct. 1978) and the TVLF signals have not been located in the "quick look" data. Dowden estimates that 20 watts radiated by the TVLF system could result in a field at GEOS of about 5 microvolts/meter. However, transmission is highly dependent upon conditions in the magnetosphere, so failure to find the signals in the "quick-look" data is not significant.

The GEOS satellite VLF data also is recorded on "high speed tapes" which have an ultimate sensitivity considerably better than is available with the "quick-look" data system. The "high speed tapes" seem to have slow circulation time between agencies, and some are more than 10 months overdue at the laboratories which will be looking for signals from tests with the one kilowatt French transmitter.

The time span of transmissions using the TVLF system and the Sortland line as an antenna was from 27 September to 4 October, 1978, UT days 270 through 277. Details of the transmissions are shown in Appendix I. It was hoped that transmissions could be made to the GEOS, S3-3, and ISEE satellites. however, S3-3 passes came during business hours which was a time when transmission was restricted. The ISEE transmission was completed on schedule. However, the data acquisition station in Spain was down resulting in a loss of data, and therefore the GEOS satellite "high speed" data is the remaining possible source of data from the 1978 TVLF transmissions.

5.0 THE TELEPHONE PROBLEM

It was recognized from experiments conducted by Dick Barr, DSIR, Christchurch New Zealand, (private communication) that the use of transmission lines as VLF antennas could be noticed by telephone users. Informal discussions during a meeting of the ATP (Andoya Transmiter Project) committee at Helsinki in August, 1978 addressed the problem of telephone interference. It was believed that the chances of serious interference was minimal because the radiated power was expected to be only a few watts.

In March, 1978 Professor M. Garnier, University of Paris, operated with one kilowatt of VLF power using the 22 km Andoya transmission line with no indication of interference with telephones. As soon as the TVLF system was placed into operation on 27 September, telephone calls were made from Konstadbotn to Andenes, and from Lodingen to Andenes. The 1,525 Hz signal was audible, but not sufficient to prevent normal telephone conversations.

On the evening of 30 September, 1978, the son of the Konstadbotn Power House engineer visited the TVLF installation and said there were several reports of the TVLF tone on the telephones close to the Strand transmission line. At that time the TVLF operators established the policy to transmit a "minimum annoyance" pulse pattern, one which had sufficient "off" time to allow emergency telephone messages to be transmitted, and a very short "on" time. As soon as practical, on Sunday morning, October 1, the Andoya Rocket Range personnel were advised of the situation. The range personnel suggested the problem might result from a few telephone subscribers with improper grounds or unbalanced lines. It was then decided that the "minimum annoyance" pulse patterns would be continued, and most of the transmissions would be scheduled for late at night when it was expected phone usage would be minimal.

On October 2, Rocket Range personnel advised that complaints of telephone interference were increasing. On October 3, a controlled test was conducted with the Lodingen Telephone Company cooperating with their instruments. Tests were made with cw (continuous wave) signals at 20, 30 and 40 amperes. Upon the conclusion of the tests, the phone company stated that undesirable interference existed at all levels of antenna current, and they suggested we avoid business hours.

Three hours of "minimum annoyance" transmissions were made with the assistance of Norwegian Scientists during the early morning hours of 4 October. Later in the morning of 4 October, the Rocket Range personnel received a Telex from the Oslo Headquarters that ordered all transmissions to cease. Further information supplied indicated that interference was observed at a considerable distance from the Sortland transmission line and particular concern was expressed regarding a PCM (pulse code modulation) system and a Maritime VHF radio.

On October 5, an all day meeting was held at the Rocket Range at which a plan was devised to break the Strand line outside the town of Siegerfjord, the largest town near the Strand line and the source of numerous complaints, and conduct a test with telephone company instruments on their critical circuits. It should be stated that all parties involved, including the Norwegian Teledirectorate, demonstrated a strong compassion and cooperation for allowing the scientific experiments to continue.

On October 6, the line was shortened. Low level tests indicated the open circuit resonance was at 2.7 kHz (as compared to an estimated 2.5 kHz). In accordance with our agreements of October 5, current was to be limited to 5 amperes. A 5 minute test was conducted at 5 amperes, after which the telephone company notified us that we were 20 db over the allowable level for interference. Presumably 1/2 ampere would be the acceptable level. While there is some uncertainty regarding the impedance, the 1/2 ampere level indicates a power dissipation of approximately 5 watts, and a radiation level of 100 microwatts.

Subsequent to the tests it was requested that, in the future, application to perform transmissions should be made to the Teledirectorate. Since review of applications to transmit takes some time, it was clear that further VLF transmissions were not feasible until another antenna was located, and coupling to telephone systems was measured.

In retrospect, it should be stated that the population density as inferred from our maps was significantly underestimated. The location of major telephone lines between the Strand line (with outgoing VLF current) and the fjord, which carried or confined the return current to the area of highest population density, was highly conducive to VLF coupling either from earth potentials, electrostatic coupling or magnetic coupling. The telephone lines themselves were likely to have resonances, which would make coupling effects worse since the lengths were similar to the Sortland line.

The annoyance factor was underestimated at first because it was not realized that the telephones in the area lacked bells, and signaling was done by tones to the subscriber's phone. Therefore the VLF signals came through even if the telephone was hung up. Furthermore the town of Siegerfjord is one of the few in the world with a manual switchboard and the VLF tones were an irritation to the operators who must spend their shifts wearing headsets.

Two important facts were not appreciated as they were discussed in the GEOS planning stage: (1) radiation below 10 kHz does not require a frequency allocation, it does require authorization, and (2) electromagnetic fields can cause interference even though the associated radiation is negligible. There could be minor variations in regulations in different countries; however, the wording and intent are adopted at international meetings, and the regulations are essentially uniform in those countries that are members of such groups.

The Norwegian experimenters will obtain the approval of the Norwegian Tele-directorate prior to conducting further VLF transmissions. Telephone coupling tests will be completed before high level transmissions are started on a new transmission line.

6.0 FUTURE PLANS

There is continuing interest in establishing a VLF transmission capability from Norway. In a Telex dated 21 December, 1978, Jan Holtet, University of Oslo, states that contact has been established with a power company in Tromsoe that is willing to allow use of a nearby power line which runs in mountain terrain, and that the University of Paris people are willing to do 1 kW transmissions when permission has been obtained from the Teledirectorate. It should be noted that interfering fields and ground currents from a 1 kW transmitter are 1/10 those of a 100 kW transmitter, and results from the smaller transmitter may be extrapolated to the larger one with confidence. Enough data has been obtained from the past impedance measurements to allow good estimates of tuning requirements for another transmission line, although the frequency and impedance of resonances should be checked to see if the line is electrically well behaved.

Although use of an established power transmission line is the most promising solution to the antenna problem, alternate solutions have been considered including the possibility of constructing a VLF long wire (20 to 30 km) antenna on poles. The poles would have to be high enough to allow circulation of animals, and minimize the danger from human contact. In general it is felt that land acquisition problems and construction costs are incompatible with funding availability.

A modification of a dedicated line, laying an insulated cable on the ground or on the snow, was discussed. Some consideration would have to be given to near field dielectric losses, and high mechanical integrity, i.e., safety of casual passersby.

A third alternate would be to utilize the Max Planck Institute for Aeronomy Ionospheric Heating experiment at Ramfjordmoen, near Tromsoe, Norway, as a VLF transmitter. Reference 2 suggests that, when electro-jet conditions are satisfactory, from 100 to 500 watts could be radiated at 1 kHz. Good progress was observed in the installation of the Max Planck heating equipment, however the operational date is uncertain until start-up problems, if any are identified.

7.0 SUMMARY

The 100 kw TVLF system was transported to Norway, and placed into operation with a 34 km 60 kV transmission line as a VLF antenna. Impedance measurements indicate return currents were probably affected by a fjord which was approximately 1000 meters from the 60 kV line. Field strength measurements at a distance of 80 km indicated a radiated power of 0.7 watts. Four days of transmissions to the Satellite GEOS did not result in observable signals in the "quick look" data, although GEOS VLF receiver data with considerably greater sensitivity is forthcoming. Interference with the Norwegian phone system was reported, and was attributed to the location of the telephone lines between the 60 kV line and the fjord.

Alternate methods for VLF transmissions to satellites from Norway include location of a transmission line remote from telephone lines, laying out a long wire antenna on the earth, or using the Max Planck equipment near Tromsoe for VLF modulation of the electrojet. Arrangements are progressing for use of another transmission line near Tromsoe, however, other alternatives are receiving careful consideration.

REFERENCES

M. H. Dazey and H. C. Koons, Impedance and Radiation Resistance of the Andoya. Norway, 60-kV Transmission Line, Aerospace Report No. ATR-78(7578)-1., 30 November, 1977.

R. L. Dowden, Private Communication, VLF Generation by the MPAE Heating Experiment, November 1978.

APPENDIX

TRANSMISSION LOG OF THE TVLF TRANSMITTER/SORTLAND LINE

27 Sept. - 4 Oct. 1978

The standard operation conditions were 40 amperes antenna current at 1525 Hz unless indicated. Times are in UT (Universal Time). Frequency was phase stable unless marked "Engineering Test". Transmissions started on even minute, but may have stopped a minute sooner than indicated below.

The on-time is given first, then repetition rate, i.e., 10 sec/30 sec would be 10 second pulses repeated every 30 seconds.

Description of other pulses are given at the end of the log.

27 Sept., UT Day 273
1200 - 1530 Intermittent Engineering Tests, 30, 40 amperes
1530 - 1610 30 Sec/60 Sec engineering Test, On at 10 sec past minute

28 Sept. UT Day 274
1000 - 1340 Intermittent Engineering Tests, 15 to 60 amperes
1340 - 1400 Engineering Tests 30 sec/60 sec

29 Sept. No transmissions

30 Sept. UT Day 273
2035 - 2041 cw
2051 - 2133 Porcupine/60
2133 - 2140 1/8 sec/1/2 sec
2140 - 2200 Off
2200 - 2300 Porcupine/30

1 Oct. UT Day 274
1600 - 1720 10sec/60 sec
1720 - 1830 10sec/30 sec
1830 - 1920 1sec/5 sec
1943 - 1953 Off
1953 - 2022 1825 Khz, 20 amperes 1sec/5sec
2022 - 2030 Off
2030 - 2106 Pattern 81
2106 - 2243 1sec/5 sec
2243 - 2252 Off
2252 - 2400 1sec/5sec

2 Oct. UT Day 275
0000 - 0220 1sec/5sec
0220 - 0300 10 sec/30 sec
0300 - 0857 Off
0857 - 1130 1 sec/5 sec
1130 - 1507 Off
1507 - 1721 10 sec/60 sec
1721 - 1803 Off
1803 - 1816 10 sec/60 sec
1816 - 1901 Porcupine/60

3 Oct. UT day 276
1303 - 1335 Intermittent cw tests, 20,30,40 amps. (Telephone tests)
1335 - 1442 Off
1440 - 1443 Intermittent cw tests, 30, 40 amps.
1443 - 1444 cw, 30 amperes, 4500 Hz

4 Oct. UT Day 277
0215 - 0221 1 sec/5 sec 20 amps
0221 - 0319 1 sec/5 sec/40 amps
0319 - 0400 Off
0400 - 0442 10 sec/60 sec
0442 - 0447 1 sec/2 sec 4525 Hz, 15 amps
0447 - 0501 1 sec/2 sec 4525 Hz, 20 amps
0501 - 0523 5 sec/30 sec 4525 Hz, 20 amps

Porcupine/30 and Porcupine/60 consist of a 4 second pulse sequence, six pulses with on-times as stated and off-times as in parentheses, in fractional seconds: 1/8 (3/16) 3/16 (1/4) 1/4 (1/4) 3/8 (3/8) 1/2 (1/2) 1, then off for the rest of the period with 30 or 60 seconds repetition rate as indicated.

Pattern 81 is a series of pulses with varying lengths and amplitudes repeating every 100 seconds.

cw: Continuous wave, sine wave of constant frequency and amplitude.

APPENDIX C

KAFJORD, NORWAY TRANSMISSION LINE

VLF ANTENNA TESTS, 1979-1980

(M. H. Dazey)

ABSTRACT

The 100-kW Transportable Very-Low-Frequency (TVLF) system was used at Kafjord, Norway, for transmissions to the SCATHA and GEOS spacecraft. A 22-kV 14-km long transmission line was used as an antenna. Modifications were made in the line to reduce telephone interference, and components were designed and installed to reduce the resonant frequency, and increase the antenna current. Final practical operating current was 40 amperes at 1280 Hz which resulted in power dissipation of 72 kW and an estimated radiated power of 29 watts.

Background

The cost of a very-low-frequency (VLF) antenna is usually a major portion of the operating costs when performing magnetospheric experiments with VLF transmitters.

The members of the GEOS S-300 Experiment Scientific Board proposed using power transmission lines for antennas in a program to transmit VLF signals to the GEOS satellite. A 60-kV line was made available for tests at Andoya, Norway. Impedance measurements indicated that the line would be satisfactory as an antenna, however, local residents experienced troubles with appliances which were serviced temporarily with a 22-kV line. A 60-kV line was located in Konstadbotn, Norway which did not require customers to receive service from an inferior line and preliminary transmissions were made using the 100-kW TVLF transmitter running at currents as high as 50 amperes. Severe telephone interference was experienced. This was attributed to the fact that the line ran within a few hundred meters of a fjord, and most of the telephone subscribers had residences between the line and the fjord.

A third line was located in a remote part of Norway, about 300 km from Tromso near the town of Kafjord. The line was approximately 15-km long and there were a few telephone subscribers near the Kafjord end of the line. Low level tests indicated serious telephone interference in the nearby residences. Since the residences were all close to the transmitter end of the line, a test was made with the first 3.6 km of the line 'floating' above ground with the current being inserted into the ground at the 3.6-km point. Tests with subscribers and the telephone switchboard indicated that currents considerably above 50 amperes could be used without causing interference in the telephone system.

The Operating Mode of Transmission Line Antennas

In the simplest configuration, a transmission line antenna can be considered a rectangular loop antenna with current going out on the transmission line wires, returning to ground at the far end, and returning in the ground back to the low potential side of the transmitter. When VLF currents travel in the ground they penetrate large distances because of the skin depth phenomenon and the low frequencies involved. Therefore in its simplest form the area of the loop antenna is given by multiplying the length of the transmission line by the skin depth at the frequency of interest.

An early concept of a transmission line antenna was the Beverage antenna which utilized a terminating resistor as a load at the far end of a long wire to avoid detuning and high voltages which could result from resonances. If the line insulators can tolerate the high voltages, more current can be obtained by operating the line at a resonant frequency, and the terminating resistor is eliminated as a source of power loss.

In the interest of safety and ease of design high-power transmitters are usually operated at high currents and relatively low voltages, which constitutes a low output impedance. A transmission line a quarter of a wavelength long with an open circuit at the far end provides a low impedance for a transmitter and is the preferred [illegible]ating mode.

Our studies indica[illegible] [illegible]hat [illegible]F currents in the ground encounter a resistance per unit length, R_e/m, which is independent of the earth resistivity and is only a function of frequency, f. The resistance value appears to be $R_e/m = 10^{-6} \times f$ ohms/meter where f is the frequency in Hertz.

In addition to the resistance described above, there is an added resistance when ground stakes are used to connect the low potential side of the TVLF system to the earth. This resistance is caused by current concentrations near the stakes and is a function of earth resistance, the number of stakes used and their placement. For simplicity we assume that the ground insertion resistance is independent of frequency. Based on our measurements, the value can be as low as a few ohms or as high as 100 ohms.

An advantage of a quarter-wave open-circuit antenna is that only one connection to the earth is necessary.

In general, when a transmission line is provided the quarter wave resonance does not occur at a desired frequency. For transmissions to the SCATHA and GEOS satellites the desired frequency was about 1300 Hz, based on the expected electron gyrofrequency at the location of the spacecraft. We find the typical propagation velocity in transmission line antennas to be about 0.7 the speed of light for the lines measured in North Norway. The desired length of a transmission line for quarter wave resonance is then given by:

$$\ell = \frac{3 \times 10^5 \times .7}{4 \times 1300} = 40 \text{ km}$$

As a practical matter, it is difficult to arrange the use of power transmission lines because of power company constraints, and the lines that have been made available are usually shorter than 40 km. The shorter lines may be electrically lengthened by adding the proper components.

In the 1979 campaign, the Kafjord line was lengthened by adding capacitors at the far end. There were several voltage, frequency and current requirements for the capacitors, however, special units were obtained that

functioned satisfactorily. The capacitor current had to be re-inserted into earth, requiring a second grounding connection. The capacitor ground connection was made in inhospitable terrain and added considerable series resistance to the complete system.

In the 1980 campaign, a special inductor was constructed at the TVLF transmitter site and connected in series with the transmission line achieving the necessary reduction in resonant frequency with minimal increase of circuit resistance.

Details and performance results of the TVLF-antenna combination are discussed below.

Electrical Characteristics of the Kafjord Line

It is desirable to determine the electrical parameters of transmission lines being considered for VLF antennas for a number of important reasons. The design of the tuning elements, if necessary, must be based upon the expected impedance of the line and the desired operating levels of voltage and current. The series resistance, R_s, determines how much antenna current can be supplied by a power amplifier with a given amount of power and a known output impedance. The characteristic impedance is related to the skin depth in the earth and estimates of this parameter allows one to determine the expected radiated power.

Figure 1 illustrates schematically three of the Kafjord, Norway transmission-line antenna configurations. Note that in all three cases, 3.6 km of elevated line was used to transmit the power to the 10.6 km of line which was the actual antenna. Impedance measurements were made in all three configurations and estimates of inductance/meter, capacitance/meter, characteristic

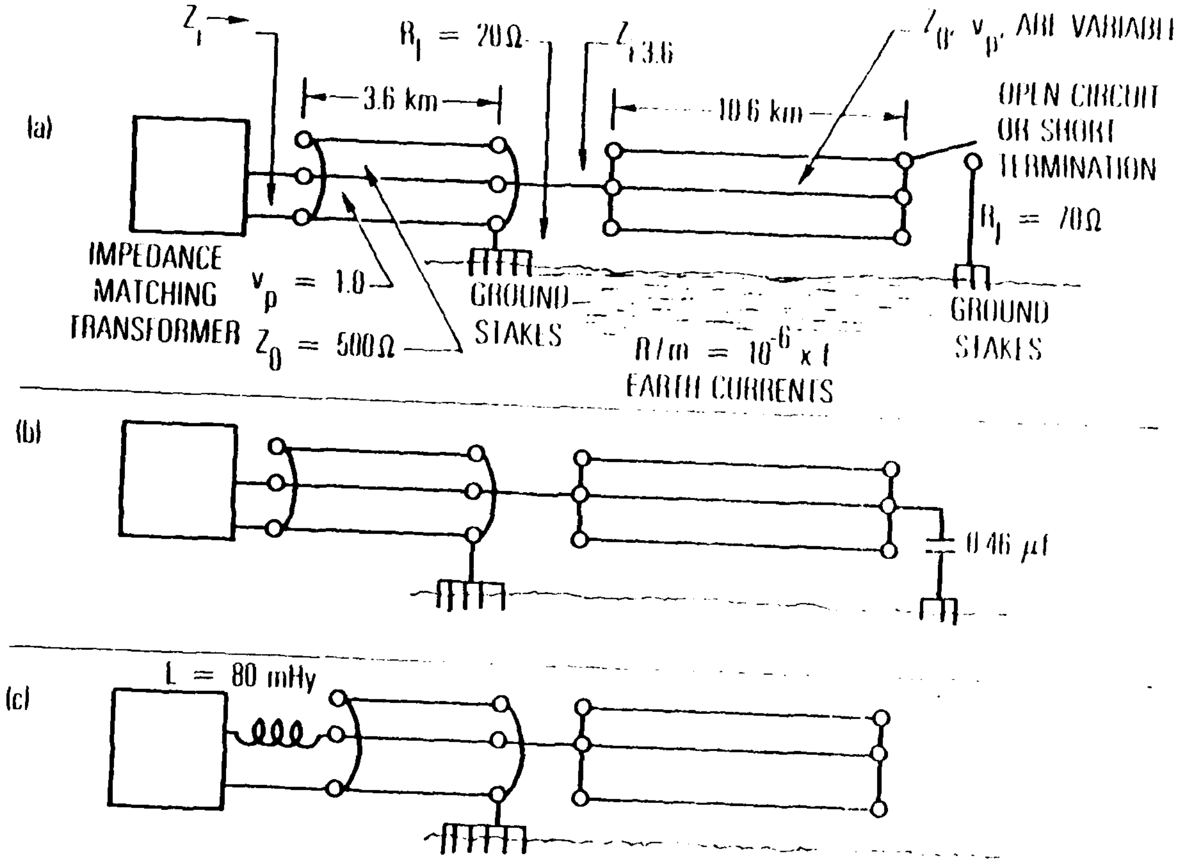

FIG. 1. Kafjord line; (a) Test configuration, resonant frequency - 3.8 kHz, (b) capacitive tuning, resonant frequency 1.3 kHz, (c) inductive tuning, resonant frequency 1.3 kHz.

impedance, velocity of propagation, skin depth in the earth, and earth resistivity were made as a function of frequency.

Impedances were measured as described by Dazey and Kuhns (1977). The measurement technique provides the modulus of the impedance, rather than the reactive and resistive terms, although at points of inflection in the curves, one can assume the impedance is purely resistive. The skin depth varies significantly with frequency and this causes significant changes in the characteristic impedance and the velocity of propagation. Since the total line included a 3.6-km portion with fixed impedances it appeared that there were too many variables to achieve an analytical solution, so trial-and-error curve fitting methods were adopted.

The short circuit and open circuit impedance values of the Kafjord line are shown in Figures 2 and 3. The analytical expressions for the short circuit and open circuit transmission lines are shown below:

The general transmission line formula is:

$$Z_i = \frac{Z_o\,(Z_L \cosh\theta + Z_o \sinh\theta)}{Z_o \cosh\theta + Z_L \sinh\theta}$$

where Z_i = input impedance of line in ohms

Z_o = characteristic impedance of line

Z_L = load at the end of the line

θ = ele-trical length of line at the frequency of interest.

For Figure 1a, Z_L = 70 ohms for the short circuit case and infinity for the open circuit.

The input impedance of the 10.6-km section of the line, that is the impedance looking into the line at the 3.6-km point, is given by the above

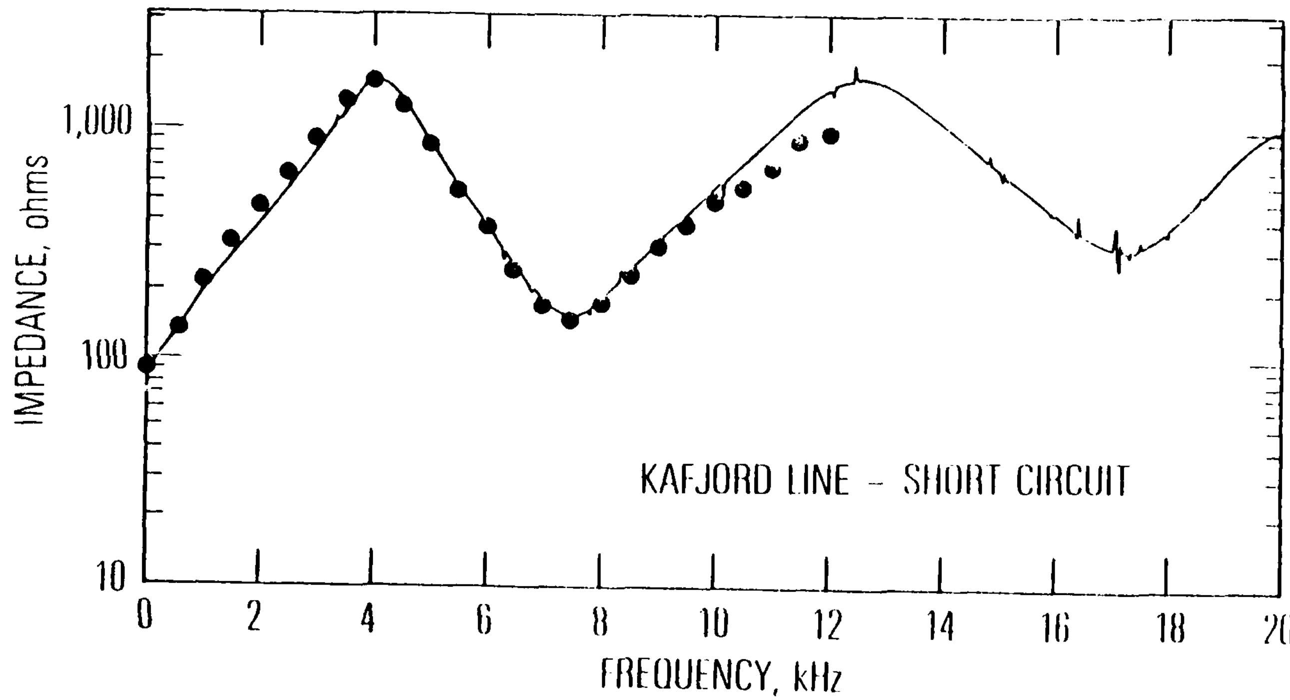

FIG. 2. Short circuit impedance of the Kafjord line.

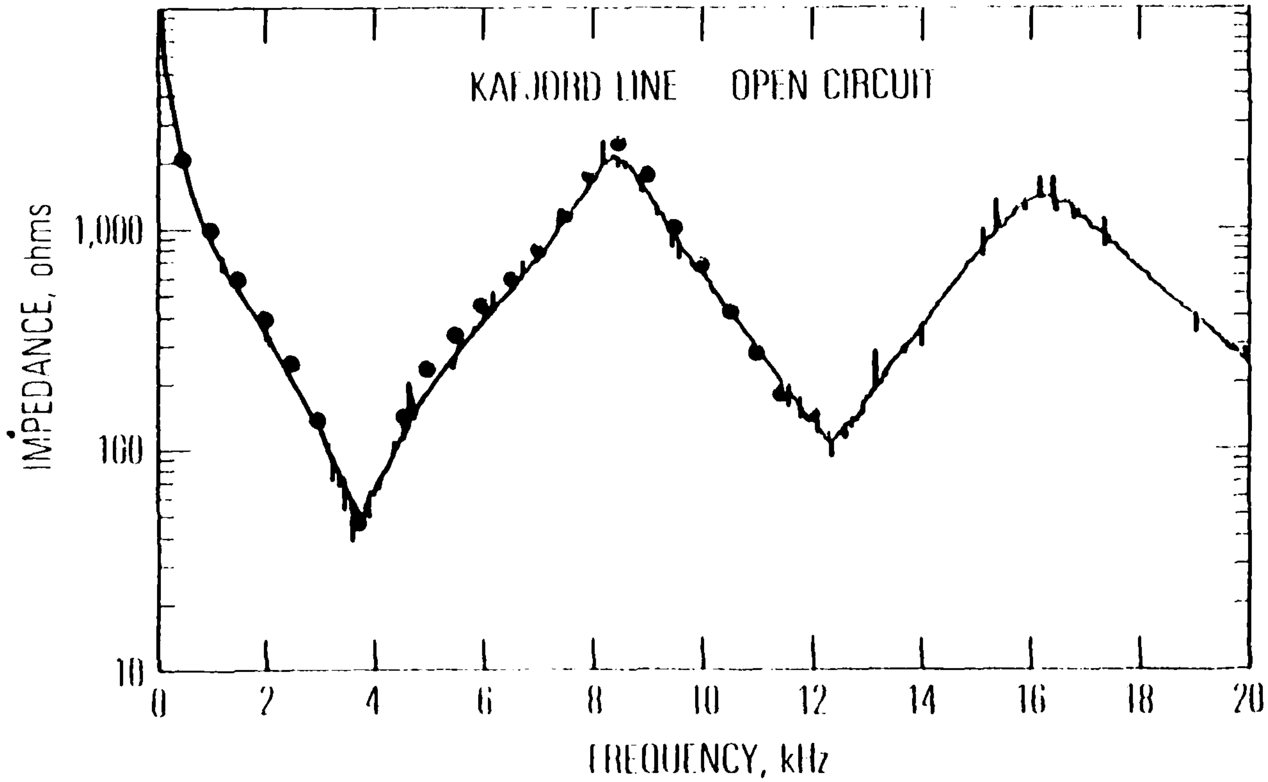

FIG. 3. Open circuit impedance of the Kafjord line.

expression with the proper loads substituted. If we call this impedance $Z_{i3.6}$, we have a load resistance for the 3.6-km section of line given by:

$$Z_L = Z_{i3.6} - 20.$$

If this Z_L is substituted into the general transmission line formula, together with the new electrical lengths and characteristic impedance, 500 ohms for the 3.6-km line, we obtain the input impedances at the transmitter end of the Kafjord line. Since most of the values are complex, the input impedance is complex. Therefore the total magnitude, or modulus, must be obtained for comparison.

The transmission line expressions were programmed in a TI 59 calculator. The assumptions and procedures used for the trial and error fitting were as follows:

1. The earth resistance was assumed to be given by $R_e/m = 10^{-6} \times f$ ohms/meter.
2. The value of the insertion resistance at the 3.6-km point was estimated from the first minimum of the open circuit impedance curve by subtracting the earth resistance.
3. The value of the insertion resistance at the short circuit, or far end of the line, was estimated from a somewhat risky extrapolation of the open circuit impedance to zero frequency, and subtracting the insertion resistance at the 3.6-km point.
4. The 3.6-km section of line was assumed, based on wire diameter and spacing, to have a constant impedance of 500 ohms and a propagation velocity of 1.0, with negligible resistance.

5. Estimates were made of Z_o and v_p in the region of 4 and 8 kHz, the frequencies of resonances and anti-resonances in the short circuit and open circuit cases. In general, the low impedances represent essentially the series resistance, R_s, of all elements, as modified by the 3.6-km section of line. The high impedance represents the value of:

$$Z_i = \frac{Z_o^2}{R_s}$$

which is mainly dominated by the value of Z_o. The location of the minima and maxima are determined by v_p. As used in this report v_p is the propagation velocity divided by the velocity of light, c, in free space.

6. Values of Z_o and v_p were tried until good fits to the experimental curves were obtained. That is, the peaks and dips had proper magnitudes and frequencies. This was done at 4 kHz, and repeated at 8 kHz.

7. The inductance/meter, L/m, and capacitance/meter, C/m, were then determined from:

$$L/m = \frac{Z_o}{c\ v_p} \qquad \text{Henrys/meter}$$

$$C/m = \frac{1}{c\ Z_o \times v_p} \qquad \text{Farads/meter}$$

The results from the above assumptions and the curve fitting are shown in Table 1. The calculated values of the capacitance increased and inductance decreased with frequency, as expected, since the ground currents flow closer to the conductor as the frequency is increased. The experimental data is not sufficiently sensitive to provide the functional relationship between inductance, capacitance, and frequency, so a linear relationship was assumed.

Table 1. Kafjord Line Impedance Parameters

Parameter	Value
Inductance/m, Henrys/meter	$2.16 \times 10^{-6} - 7.5 \times 10^{-11} f$
Capacitance/m, Farads/meter	$1.13 \times 10^{-11} + 3.5 \times 10^{-16} f$
Insertion Resistance at transmitter end, ohms	20
Insertion Resistance at far end, ohms	70

From L and C, we can calculate Z_o and v_p as a function of frequency from:

$$Z_o = \sqrt{L/C}$$

and

$$v_p = 1/(c\sqrt{LC})$$

Curves showing the variation of Z_o and v_p with frequency, as calculated from the expressions above are shown in Fig. 4.

Capacitive Tuning of the Kafjord Line

The Kafjord line resonated at 3.8 kHz in the quarter-wave open-circuit mode. Operational requirements made it necessary to operate at 1.3 kHz, and in 1979 this frequency was obtained by adding capacitors to the far end of the line.

Simple trigonometric expressions are usually adequate for estimating the value of the capacitance required and the expected losses. Based upon earlier measurements, it was assumed that the line would have a characteristic impedance of about 350 ohms (somewhat less than the 417 ohms obtained from the results presented in Fig. 4), and a velocity of propagation of about 0.7 c.

The impedance of a short circuit line operating below its resonant frequency when measured at the open circuit end is given by:

$$Z_{oc} = j\, Z_o \tan\theta$$

where

$$\theta = \frac{360^\circ \times 14,200 \times 1300}{3 \times 10^8 \times .7} = 31.6^\circ$$

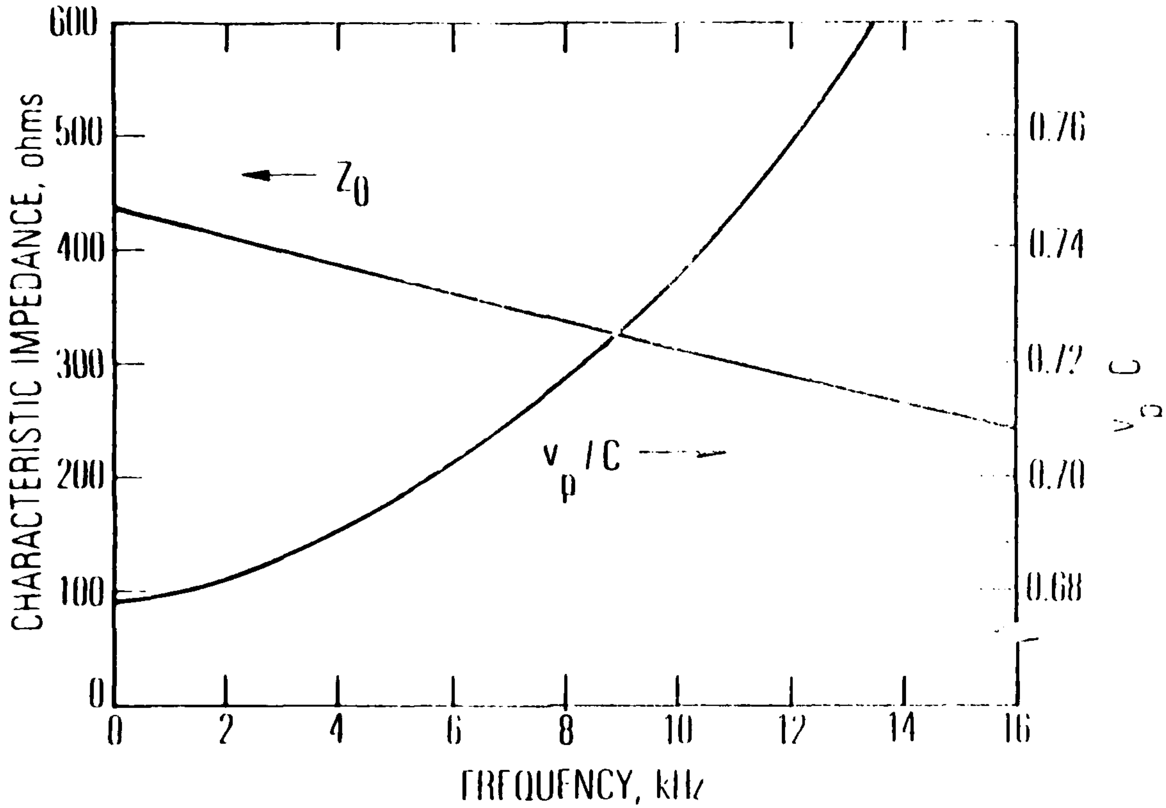

FIG. 4. Characteristic impedance Z_0 and wave phase velocity v_p/c.

Since the above value is inductive, the line can be 'tuned' with a capacitor with the same numerical value of reactance:

$$X_c = 350 \times \tan 31.6° = 215\ \Omega$$

or

$$C = \frac{1}{2\pi \times 1300 \times 215} = 5.6 \times 10^{-7} \text{ farads}$$

Operating high voltage, high current capacitors at any other frequency than 60 Hz requires special considerations and most manufacturers would prefer that you not use their products in that manner. It was possible to obtain capacitors with the standard loss factor rating, a series conductor resistance rating, and a wattage rating. From the specifications it was possible to determine an array of capacitors which could be used, although not at the maximum power desired. The capacitor specifications are given in Table 2.
It was estimated that at 1.3 kHz, the total capacitor current would be 35 amperes for an input current of 40 amperes from the TVLF system. The total voltage at the capacitors would then be 8,000 volts.

Twenty capacitors were purchased and pairs were connected in series, then ten pairs were connected in parallel, so the voltage on each capacitor was divided in 1/2 and the current was divided by 10. The losses could then be calculated for each capacitor:

Dielectric Loss = Power factor x voltage x current

= .001 x 4,000 x 3.5 = 14 watts

Conduction Loss = $(\text{Current})^2$ x conductor resistance

Table 2. Capacitors Used to Tune the Kafjord Line to 1.3 kHz

Parameter	Value
Capacitance, μF	0.1
Voltage rating, kV	13.
Power factor	0.001
Conductor resistance, ohms	0.25
Power dissipation, W	10.
Total Capacitance, μF	0.56

$$= (3.5)^2 \times 0.25 = 3 \text{ watts}$$

for a total of 17 watts. Since the capacitors were only rated for 10 watts, care was taken to operate at less than 50% duty cycle. The wattage rating is based on a 40° temperature rise. The location of the capacitors on the top of a mountain where there was a steady cold breeze would probably have allowed up to 100% duty cycle without much danger of overheating.

The equivalent series resistance of the capacitors was:

$$R = \frac{P}{I^2} = \frac{17}{3.5^2} = 1.4 \text{ ohms.}$$

The net resistance for the series-parallel array was about 0.3 ohms, which was negligible compared to the earth insertion resistance.

Figure 5 shows the impedance vs frequency curve with 0.46 uF capacitance. The minimum impedance at resonance, i.e., the total series resistance, is the parameter that determines the antenna current possible with a given amount of transmitter power. The allocation of resistance is as follows:

Insertion Resistance at 3.6 km	= 20 Ω
Ground Transmission Resistance	= 14 Ω
Insertion Resistance at Capacitors	= 50 Ω
Total	= 84 Ω

Since all the current in the line does not go through the capacitors, the apparent resistance is somewhat less than the 70 ohms determined as described in the previous section. The current which does not go through the capacitors is returned to the earth as displacement current along the length of the line.

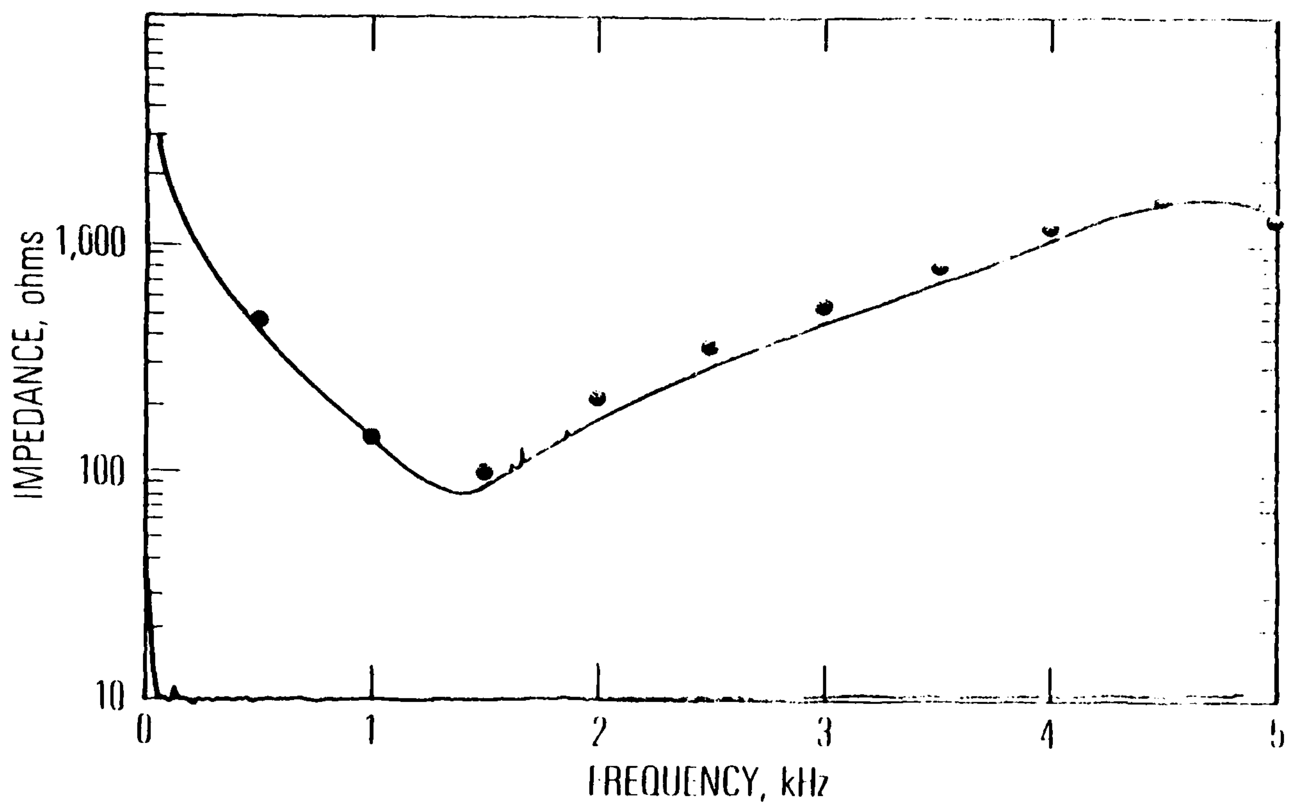

FIG. 5. Impedance of the Kafjord line tuned by 0.46 μF capacitance in series with the line to ground at the far end of the line from the transmitter.

Inductive Tuning of the Kafjord Line

If an inductor is placed between the transmitter and the transmission line, the resonant frequency will be reduced. If we take the same frequencies as in the previous section we may determine the value for this inductance.

The impedance of an open circuit line is given by:

$$Z_i = - Z_o \cot \theta = -350 \cot 31.6^\circ = -569 \, \Omega$$

Since this is capacitative, this may be tuned by an inductance with the same reactance, and the value of the inductance is:

$$L = \frac{569}{2\pi \times 1300} = .070 \text{ Henrys}$$

Typical inductors have high losses at high frequency because the conductors are immersed in their own alternating magnetic field causing eddy currents. The large equivalent series resistance may be reduced by using an 'open' construction at the expense of increasing the length, spacing and size of the conductors. The final inductor design was based on Grover (1946) and Terman (1943). The physical and measured electrical parameters of the inductor are given in Table 3.

The measured results were within reasonable agreement with the calculated values.

A 50-foot roll of soft copper tubing was sufficient for each layer. Tubes were soft soldered using a butt joint. Spacers were glass melamine. Assemblies of 12 layers were fabricated at El Segundo and shipped by air to Tromso for final assembly of the full 120 layers at the site of the TVLF transmitter.

Table 3. Inductor Used to Tune the Kafjord Line to 1280 Hz

Parameter	Value
Turns	500
Turns Layer	5
Outside diameter, inches	36
Height, inches	120
Horizontal turn spacing, inches	1
Layer spacing, inches	1
Conductor diameter, inches	0.25
Inductance, Henrys	0.073
Resonant bandwidth, Hertz	15.4
Q	82.8
Series Resistance, ohms	7.5

Figure 6 is a "Q" curve obtained from the inductor. Figure 7 is impedance curves of the line, the inductor, and the line with the inductor installed.

Note that the series resistance was lowered to 45 ohms with inductive tuning, as compared to 84 ohms with capacitive tuning, allowing currents as high as

$$I = \left(\frac{P}{45}\right)^{1/2} = \left(\frac{10^5}{45}\right)^{1/2} = 47 \text{ amperes for}$$

the 100-kW transmitter.

Skin Depth and Earth Resistivity

The skin depth of the electrical signal in the earth may be determined if the characteristic impedance and propagation velocity of a transmission line are known. Expressions that have been derived to relate the characteristic impedance of a line to the dimensions of the line, wire size, spacing, and height above ground assume a line of infinite length above a perfectly conducting plane.

For a three-wire line above a conducting ground plane, the characteristic impedance is given by

$$Z_o = 138\, \epsilon^{-1/2} [[\log(4h/d) \log \{(4h/d)\, [1+(h/D)^2]^{1/2}\}$$

$$-2\, \{\log[1 + (2h/D)^2]^{1/2}\}^2]] \qquad (1)$$

$$+ \log \{(4h/d)^3 [1 + (2h/D)^2]^{-2}\, [1 + (h/D)^2]^{1/2}\}$$

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CONTROLLED WAVE-PARTICLE INTERACTION AND VLF WAVE PROPAGATION E--ETC(U)
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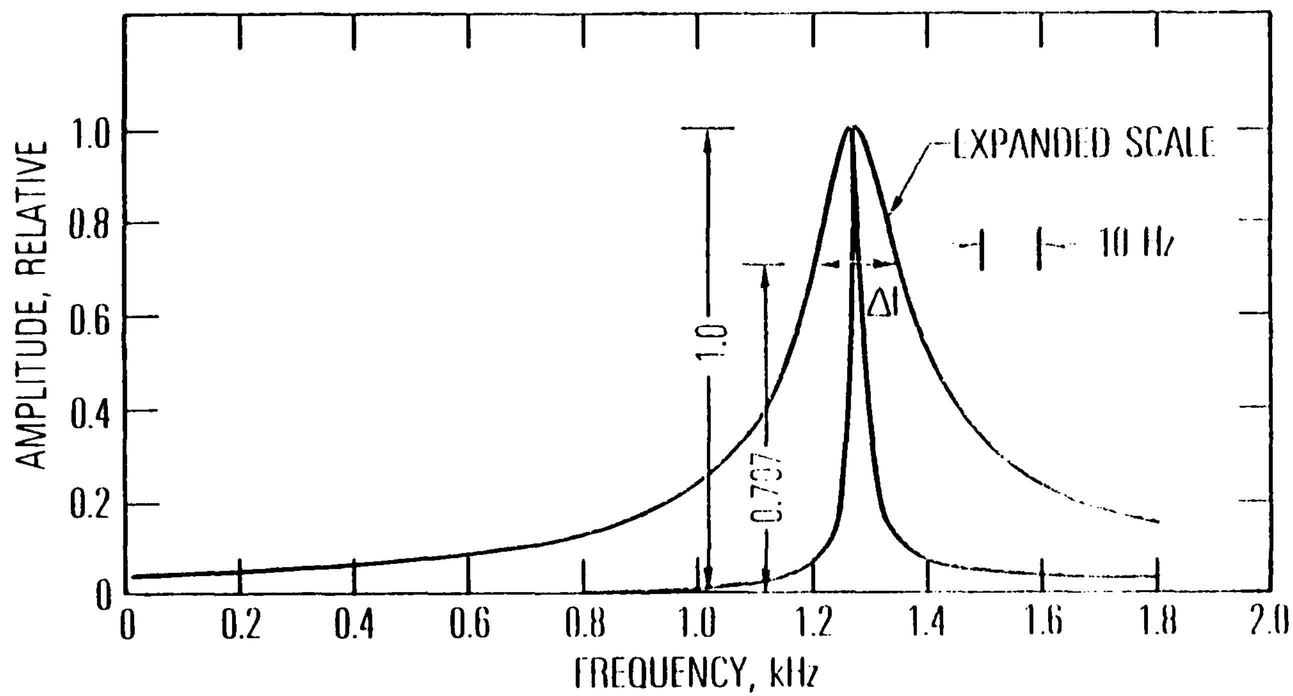

FIG. 6. "Q" curve of the Kafjord line tuned by a 70 mH inductor in series with the line at the transmitter end of the line.

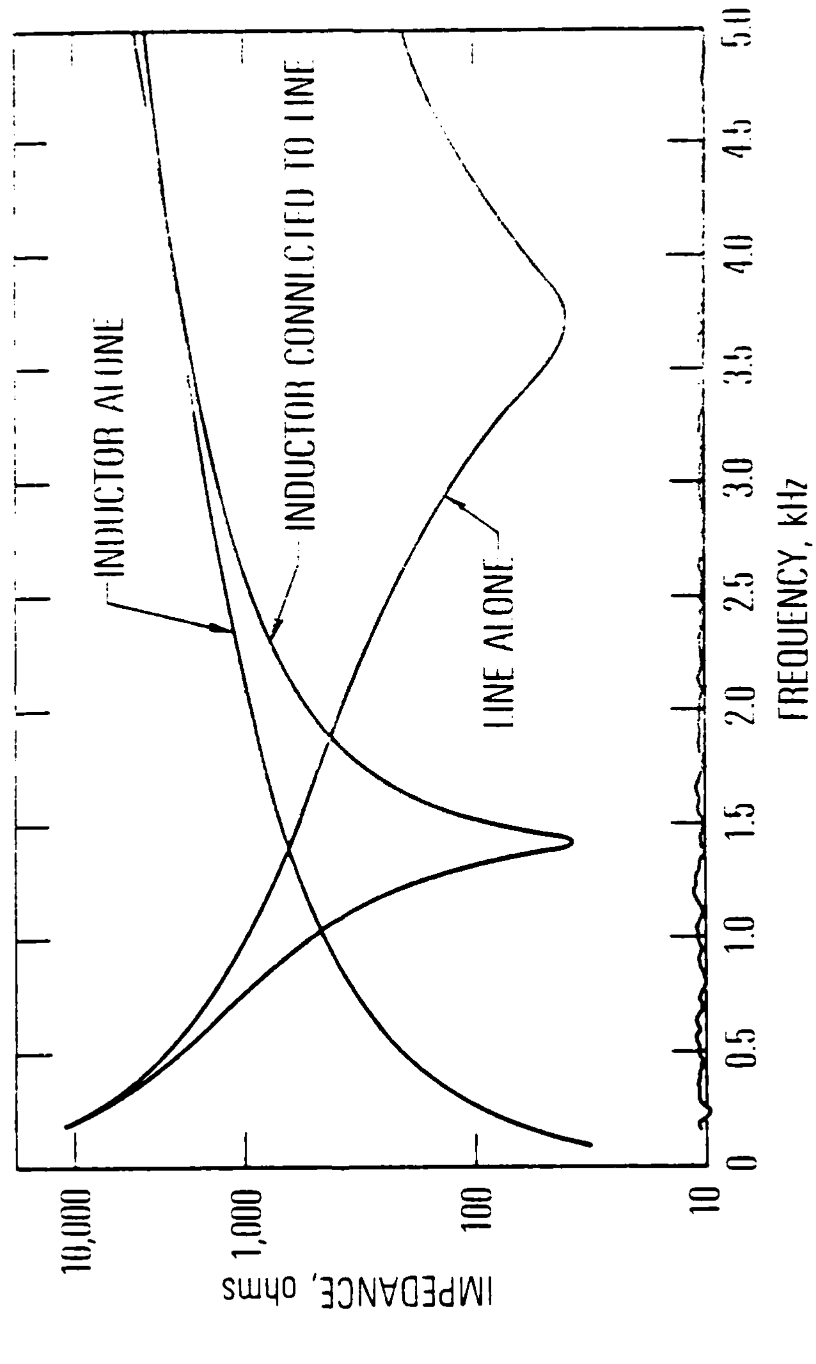

FIG. 7. Impedance of the Kafjord line in the indicated configurations.

where:

h = height above ground plane

d = wire diameter

D = wire spacing

ε = dielectric constant of space surrounding the wires.

For low frequencies and large skin depths in the earth, it is possible to disregard the approximately 9 meters of air between the transmission line and earth. If we use the velocity of propagation and characteristic impedance for 1280 Hertz, we can determine the effective depth of the current, h, from the above expression, since the relationship between dielectric constant and velocity is given by

$$v_p = (1/\varepsilon)^{1/2}$$

The parameters used to evaluate Eq. (1) are given in Table 4. The value of h is found to be 3440 meters. The relationship between skin depth, δ, and h is

$$h = \frac{\delta}{\sqrt{2}}$$

or δ = 4860 meters.

For a homogenious earth the value of the conductivity obtained from the equation

$$\sigma = (\delta^2 \pi f \mu_o)^{-1}$$

Table [illegible]. Electrical Properties of the Hafjord Line at 1230 Hz.

<u>Parameter</u>	<u>Value</u>
Wire diameter, meters	0.0037
Wire spacing, meters	1.5
Characteristic impedance, ohms	417
Velocity of propagation	0.681 c
Dielectric constant	2.16

is 3.4 x 10^{-6} S/m at 1230 Hz.

Analysis of Norwegian transmission lines using this approach appears to result in values of earth conductivity considerably smaller than the normally accepted minimum values obtained elsewhere using other measurement techniques. The low values of conductivity and consequently skin depths yield larger radiated powers than would be expected. It is not practical, within the scope of this effort, to determine the cause of the discrepancies, if they exist. Some possible sources of error include earth inhomogeniety or end effects, which may be important because the apparent skin depth is the same order of magnitude as the total length of the line.

Radiation Resistance

The radiation resistance R_r for a power line loop antenna can be obtained from (Bernstein et al., 1974)

$$R_r = \frac{\pi^3 \times 377 \times \delta^2 \times \ell^2}{2 \times h_i \times \lambda^3}$$

The value obtained for the Kafjord antenna parameters in Table 5 is $R_r = 0.018$ ohms. For a typical operating current of 40 amperes, the radiated power, $P_r = I^2 R_r$, is 29 W.

Field strength measurements were made at Lanvangsdalen and Kiruna during the 1980 campaign by the University of Sheffield personnel; however, results are not yet available. These field strength measurements, made a reasonable fraction of a wavelength from the transmission line, are expected to provide data for a better estimate of radiated power in the near future.

Table 8. Parameters Used to Compute the Radiation Resistance of the Hafjord Antenna at 1280 Hz.

Parameter	Value
Skin depth, meters	4,360
Line length, meters	11,600
Ionospheric height, meters	80,000
Wavelength, meters	234,000

[illegible]

The method of determining skin depth from impedance measurements is subject to errors resulting from the accuracy of the measurements in addition to the problem of using infinite transmission line relationships for a finite length line.

The impedance plots were made automatically, and reproduce to a line width. Operational constraints prevented making the measurement over a number of days to determine if values changed as a function of climatic conditions, i.e., rain. The impedance plots are on a logarithmic scale where a 0.1 inch error is a 10% error in impedance. The characteristic impedance and the propagation velocity, from which the effective height of the conductors and the skin depth is obtained involve algebraic manipulation of the quantities which do not cause a significant increase in error.

However, the height of the conductors, h , is a sensitive function of the characteristic impedance, Z_o, and the propagation velocity, v_p. The equation for the three-wire line in terms of h appears to be intractable, however, the equation for a single-wire line as a function of h, is given by:

$$h = \frac{a}{2} (10)^{Z_o/138 \, v_p}$$

If the value of the exponent is the order of 1.0 a 10% error in Z_o causes about a 26% error in the value of h. If however, as is the case with the Kafjord transmission line the exponent value is about 4, the error in h for a 10% error in Z_o is about a factor of 2.5.

Since the radiated power goes as the square of the skin depth, the power estimates could vary widely if there are errors in the measurement or the assumed model.

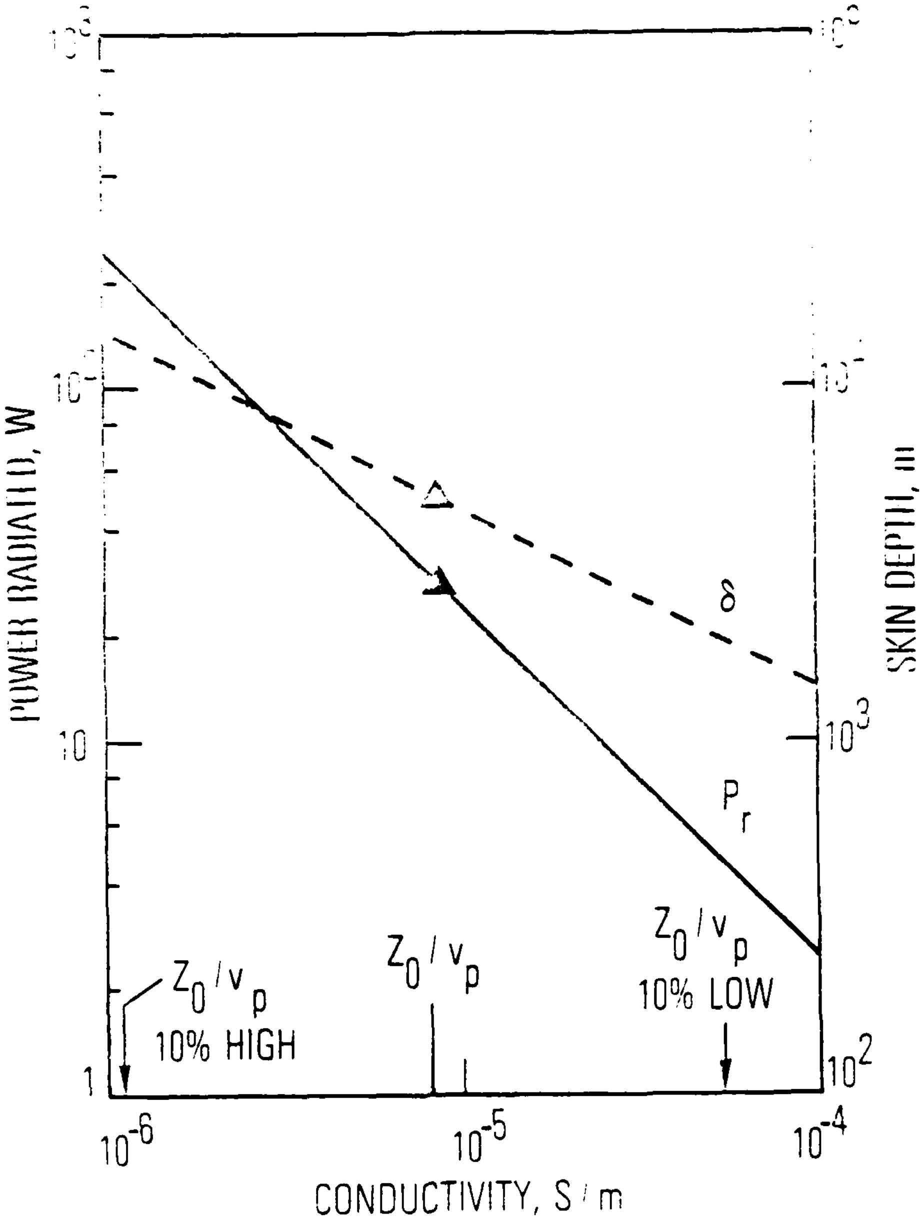

FIG. 8. Power radiated, P_r, and skin depth, δ, at 1280 Hz as a function of rock conductivity. The triangles are the result of the measurements and calculations reported here. The conductivity for 10% errors in Z_0/v_p are also indicated.

Figure [illegible] shows the spread of results that [illegible] [illegible] for [illegible] [illegible]

Conclusions

The 100-kW TVLF system was operated in Rafjord Norway ([illegible] miles from Tromso) during the summers of 1979 and 1980, using a [illegible]-km, [illegible]-kV transmission line as an antenna. The results of impedance measurements on other lines provided data which allowed calculation of both capacitive and inductive tuning elements for use in lowering the frequency to a value approximating one half of the electron gyrofrequency in the vicinity of the SCATHA and GEOS satellites.

Radiated power, estimated from the measured characteristic impedance is about 29 watts for 40 amperes antenna current. An independent estimate of radiated power will be made when field strength measurements are made available.

Acknowledgments

Dr. Harry Koons of The Aerospace Corporation has been the Principal investigator on the TVLF programs to transmit to satellites for three campaigns in Norway, and in Alaska and New Zealand. His patient support of the measurement and construction tasks has allowed the improvements described herein.

The initial impetus to use the TVLF transmitter in Scandinavia was provided by Dr. Arne Pedersen of ESTEC. The Space Acitvity Division of the Royal Norwegian Council for Scientific and Industrial Research (NTNF) was particularly helpful with numerous negotiations and arrangements with Norwegian agencies. We are especially indebted to Prof. Jan A. Holtet of the University of Oslo who devoted many months helping in the field, and working with the local and national agencies to insure success in the transmissions, to Prof. Les Wooliscroft, University of Sheffield, who was able to inspire a number of agencies to help us financially, and in addition, made the ground calibration measurements for the 1980 campaign and to R. G. Robbins, R. L. Walter, and J. Døhl who worked hard to overcome all of the equipment failures and keep the transmitter on the air. We wish to thank Prof. M. Garnier, G. Girolomi and J. Conrad, University of Paris, who made measurements and transmissions which were helpful in designing components for the larger transmitter, and demonstrated a transmission line configuration that would not cause telephone interference.

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APPENDIX D

VLF TRANSMISSIONS FROM KAFJORD (NORWAY) TO SCATHA

(M. Garnier and G. Girolami, University of Paris

H. Koons and M. Dazey, The Aerospace Corporation)

ABSTRACT

Interactions in the magnetosphere between man made VLF waves and electrons can produce either an enhancement of the wave or the generation of waves at a different frequency. Furthermore the frequency of a natural signal can be shifted by a nearby transmitter signal.

Injection of VLF waves in the magnetosphere was initiated in 1978 in Norway by both University of Paris and Aerospace Corporation. The antenna is a 15 km power line tuned at the transmitted frequency. The 1 Kw transmitter used for the phenomenons reported here drives the antenna with a maximum current of 8 Amps. The transmitted signals can be received either on board GEOS 2 or on board SCATHA, US spacecraft launched in January 1979.

The first transmission campain took place in May 1979.

Signals correlated with the transmissions were recorded on May 25th and May 27th. The transmissions consisted either in a 1280 Hz keyed fixed frequency or in a continuous wave swept in frequency from 1350 Hz to 2550 Hz.

With the first type of transmission, signals looking like PLR were recorded on May 27th from 21.42 to 21.55, then around 22.00 four examples of ASE are likely to have been triggered. On May 25th both types of transmissions triggered or enhanced hiss at a constant frequency during 1280 Hz transmission or at a variable frequency in the other case.

During swept frequency transmissions two examples of natural emissions shifted in frequency by the man made signal occured.

I - EXPERIMENTATION AND SIGNAL PROCESSING

As soon as 1975 it was proposed to try to transmit man made VLF signals to GEOS. An antenna was to be built in Sweden but because of the price of this operation it was decided to use a power line as an antenna. A first line was tested then in Norway near Andenes, in March 1978 it was possible to try transmissions to GEOS I, nevertheless the use of this line brought important

perturbations to the Norvegian power distribution network so that it was necessary to stop the experiment.

Another power line was found near Sortland and the Aerospace Corporation's TVLF transmitter was operated in October 1978 for transmissions to GEOS, an example of the signals received will be presented later. During the 1525 Hz keyed transmissions, so strong interferences with the telephone network took place, that we had to stop transmissions.

A third and last power line was proposed by Norway in 1979 near Kajford. It runs on the mountains over 15 kms and can be used all day long without any interference on the telephone network. Transmissions took place in May 1979, August 1979, May 1980 and will start again in July 1980.

Except an example for GEOS in October 1978, in this paper we will describe the preliminary results got during the May 1979 transmission campain ; during this period GEOS II was on, but the datas have not been processed yet, and the US spacecraft SCATHA launched in January 1979 was then on the Kajford magnetic field line during about 2 hours per day.

The power line used as an antenna was tuned at different frequencies from 1200 Hertz to 2500 Hertz by a variable coil. The transmitter was a 1 Kw amplifier.

Two kinds of transmissions were performed :

A) 1280 Hertz keyed fixed frequency transmissions : 4 sec ON 8 sec OFF

B) Linear swept frequency transmissions from 1350 Hz to 2550 Hz at the rate of 300 Hz every 176 seconds. This rate was chosen in order to be consistent with the sweep rate of the GEOS VLF receiver. During these swept frequency transmissions, the antenna was tuned every 300 Hz at 1500 Hz, 1800 Hz, 2100 Hz and 2400 Hz, it was then possible to get a maximum antenna current of 8 amperes. Compared to the sweeping time, the switching time of the tuning circuit was very short.

Analog tapes, provided by the Aerospace Corporation, were processed at the University of Paris. Spectral analysis was performed with a real time FFT analyser connected to a laboratory computer. It was then possible to get either

full bandwith FFT analysis or a FFT magnifying of any part of the spectrum in real time. A brightness modulation of the graphic display unit of the computer by the successive computed spectrums, enables to get the usual video spectrograms. The software written for this operation has the following property : whatever is the amplitude of the input signal, the result of the FFT is multiplied by the convenient power of 2 in order to remain inside the dynamic range of the brightness modulation. It is then possible to detect very weak signals and the spectrograms displayed on figures 1 to 5 must be read in the following way : an increase of the signal level will not bring a blackening of the spectrogram but a decrease of the whole noise level.

II - EXPERIMENTAL RESULTS

A) MAGNETOSPHERIC HISS : MAY 26th 1979.

A few samples of the spectrograms performed on May 26th are displayed figures 1 to 4. Figures 1 and 2a display the signals received between 13.36 UT and 13.50 UT. From 13.36 to 13.40 no transmission took place and the every 16 seconds switching from the magnetic antenna (maximum of noise) to the electric antenna will be noticed. During this period the spacecraft receives only a faint magnetospheric hiss between 1200 Hertz and 1800 Hertz buried in noise. A 1280 Hz transmission (B O T) begins at 1340 UT, from then the hiss level increases and its bandwith decreases (figure 2a). The amplification of the hiss due to the interaction with our transmission can reach 15 decibels. This hiss amplification no longer exists while at about 1400 starts a swept frequency transmission and the frequency of the faint natural hiss is centered around 1400 Hz. During 3 minutes from 14.02 UT to 14.05 UT when the transmitted frequency are rather close together, there is again a hiss amplification.

This amplification begins again at 14.12 UT with a fixed frequency transmission and lasts up to 14.30 UT the end of this transmission (figure 3a). The amplification is then of 15 decibels.

From 14.30 UT to 14.42 UT a swept frequency transmission, which leads to a hiss amplification from 14.34 UT, was performed. During this transmission the hiss frequency decreases from 1400 Hz at 14.34.30 UT to 1100 Hz at 14.42 UT while the transmitted frequency increases.

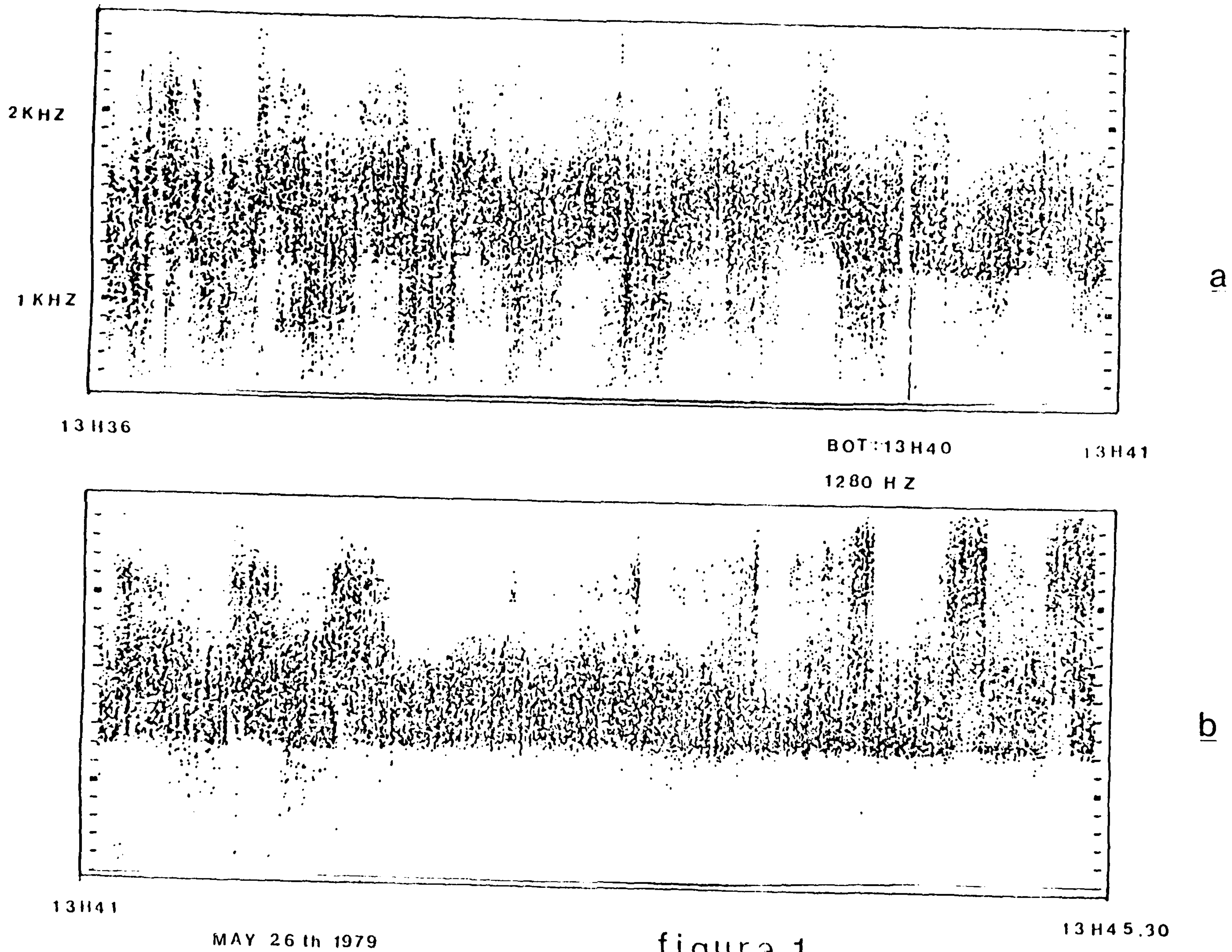

2KHZ
1KHZ
a
13H36
BOT:13H40
1280 HZ
13H41
b
13H41
MAY 26th 1979
13H45.30

figure 1

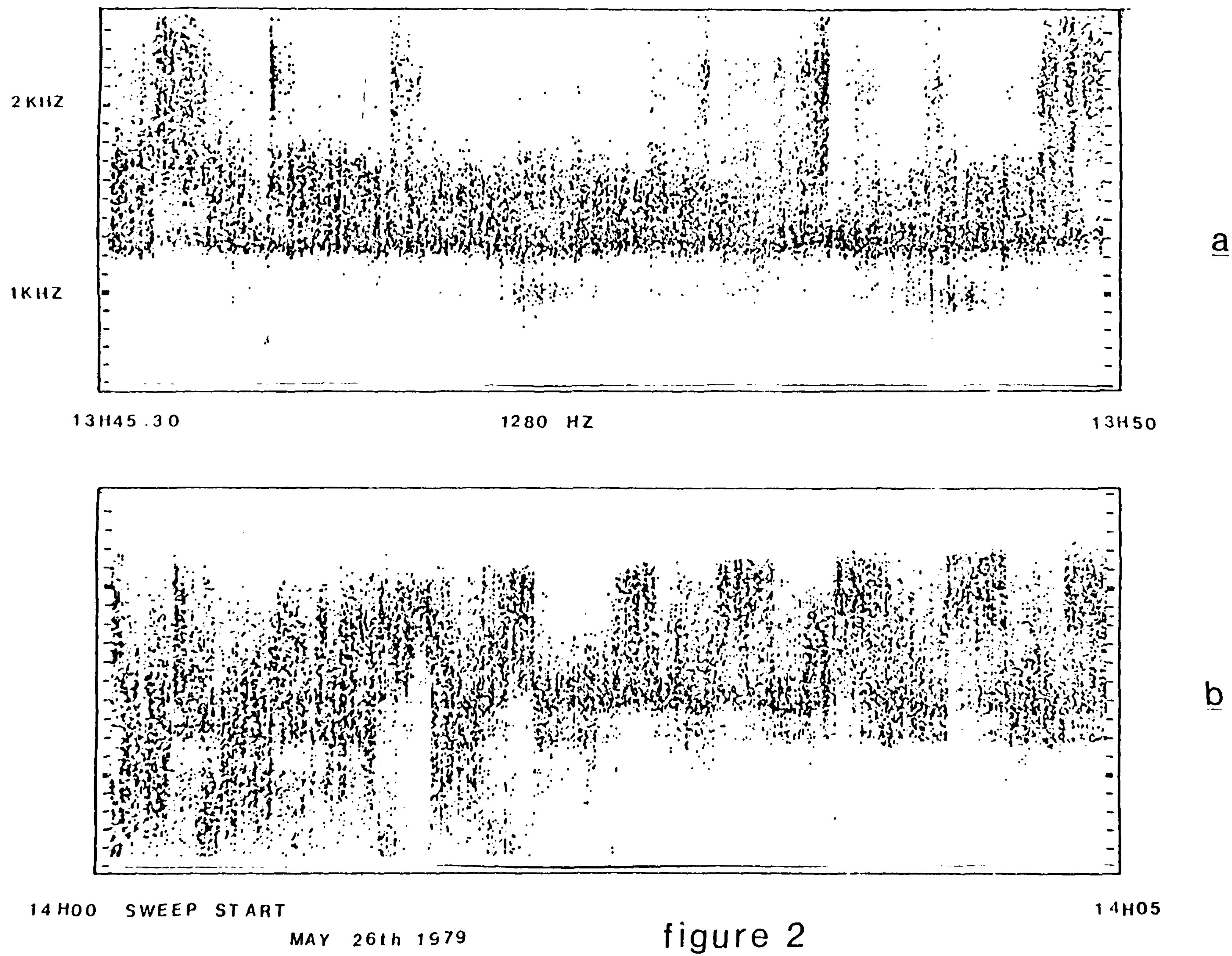
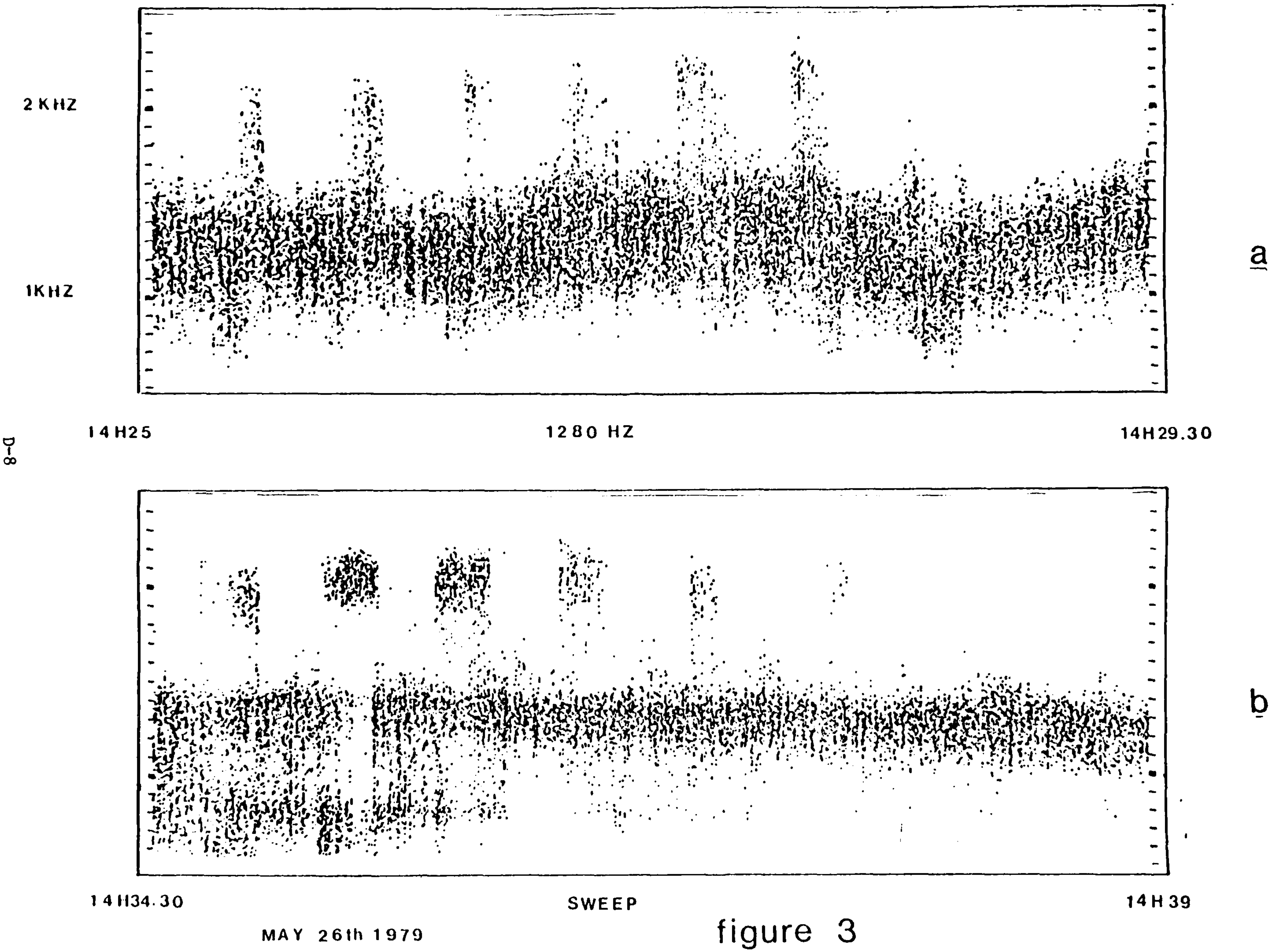

2KHZ
1KHZ
13H45.30
1280 HZ
13H50
a
b
14H00 SWEEP START
14H05
MAY 26th 1979

figure 2



2 KHZ
1KHZ
a
14 H25
1280 HZ
14H29.30
b
14 H34.30
SWEEP
14 H 39
MAY 26th 1979

figure 3

The hiss frequency is again constant and even increases slightly (figure 4b) from 14.42 UT the beginning of a new fixed frequency transmission.

From these results the evidence of a strong correlation between the transmissions and the hiss level can be concluded. The up to 15 decibels amplification starts with the fixed frequency transmissions or takes place when the frequency of the swept frequency transmission is close to the natural magnetospheric hiss one. Between 14.34 UT and 14.42 UT the amplification processes take place all along the sweep and the frequency of the magnetospheric hiss varies in connection with the transmitted frequency.

B) NARROW BAND EMISSIONS : May 27th 1979

The spectrograms presented for May 27th are the results of magnifying FFT centered on the transmitted frequency. The center frequency is 1280 Hz for fixed frequency transmissions and is sweeping during the swept frequency transmissions so that in the latter case a fixed frequency signal may lead to a negative slope as on figure 6a and to a nearly horizontal line when the transmitted sweep has been received as on figure 6b and 6c.

The horizontal lines at 1140 Hz, 1260 Hz and 1380 Hz are 60 Hz harmonics recorded on the tapes with the signals and no 50 Hertz harmonics due to the european power network are detectable.

Before 21.42 UT, the beginning of the 1280 Hz transmission, only 60 Hz harmonics and noise are detectable (figure 5). After 21.42 UT a faint 1280 Hz signal is amplified with a slight ($\pm$ 20 Hz) frequency shift. This signal which looks like the PLR described by Helliwell is likely to have been generated by the transmission. Between 21.53 UT and 21.55 UT the frequency of the emission increases - is held quite constant near 1300 Hz - then is turned around near 1350 Hz, these two frequencies being power line harmonics. This phenomenon is similar to the wave wave interaction between power line harmonics and Siple signals reported by Helliwell and al.

A steady signal at 1280 Hz is detectable after 21.57 UT and between 21.59 UT and 22.01 UT 4 examples of ASE with about a 24 seconds period are detectable only when the noise level is low, that is on the electric antenna.

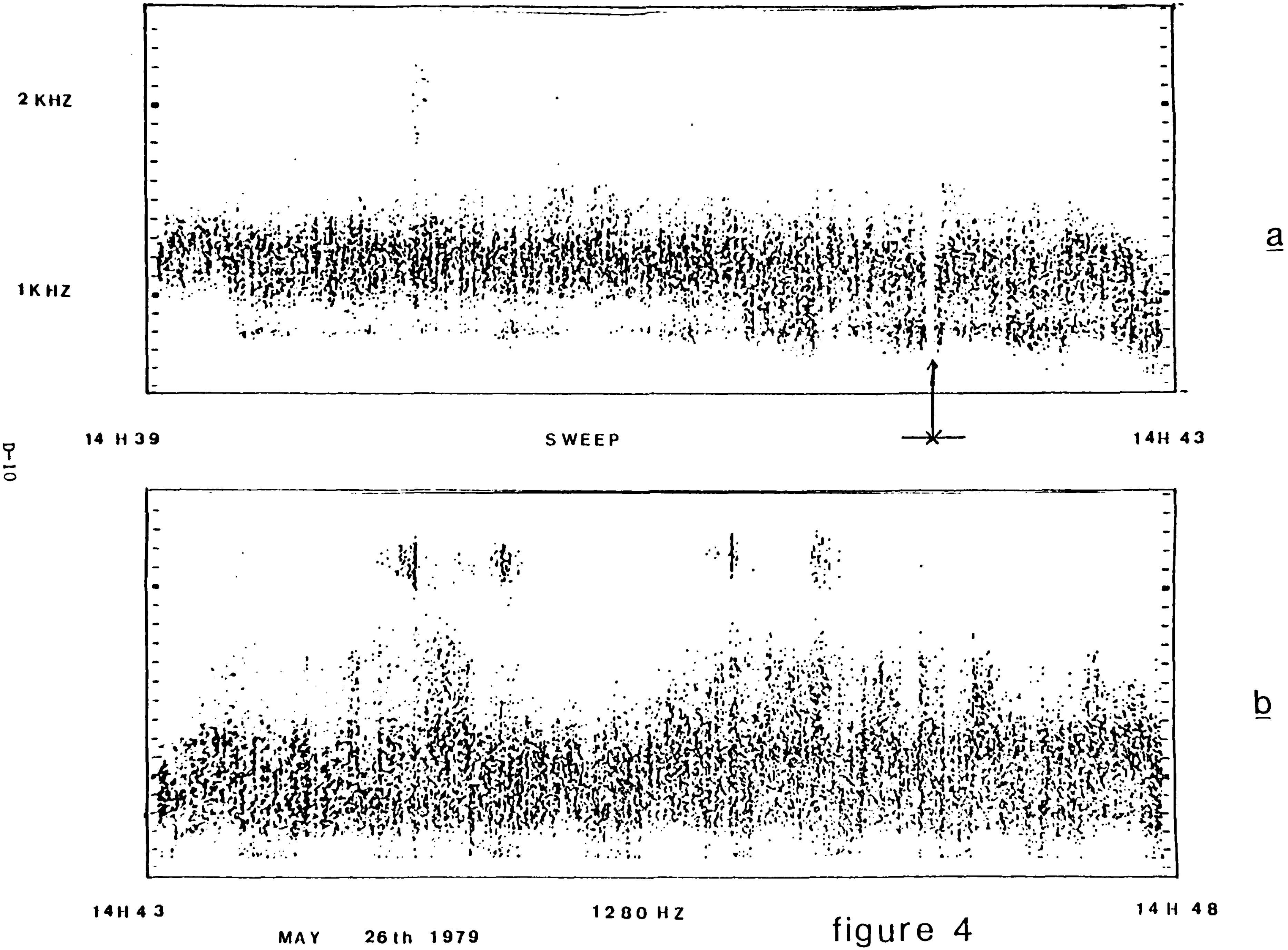
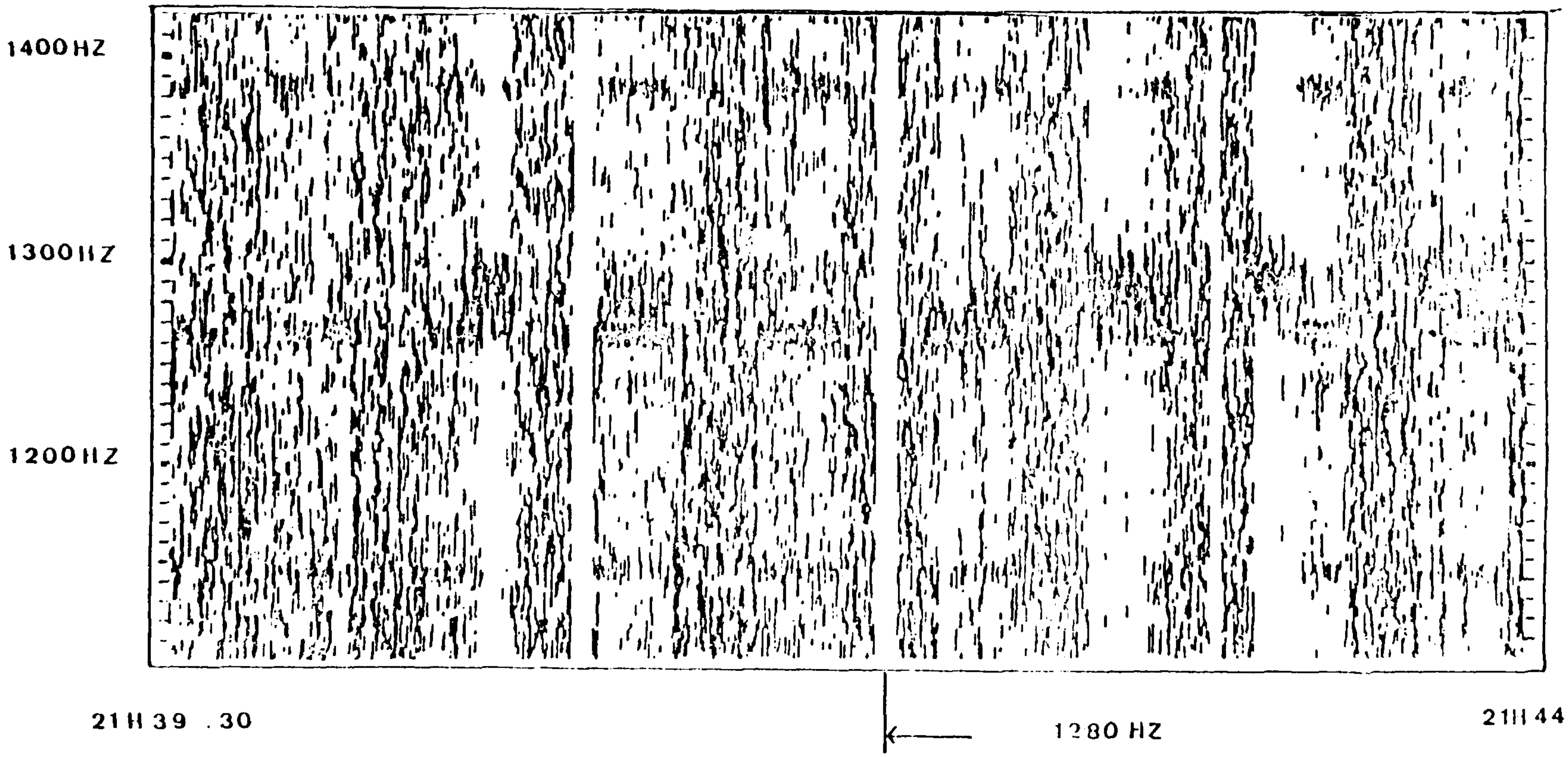

2 KHZ
1 KHZ
a
14 H 39
SWEEP
14H 43
b
14H 4 3
1280 HZ
14 H 48
MAY 26th 1979

figure 4



MAY 27th 1979

figure 5_a

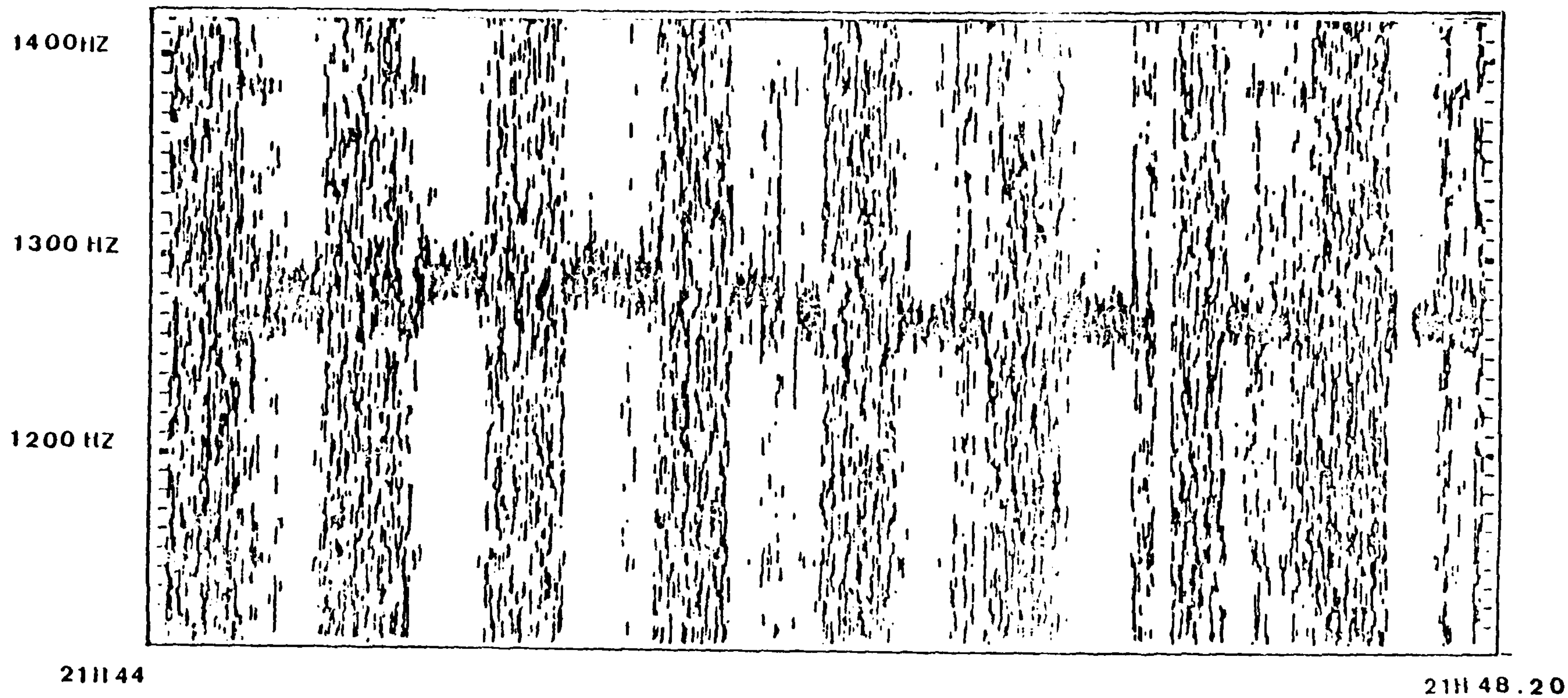


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figure 5_b

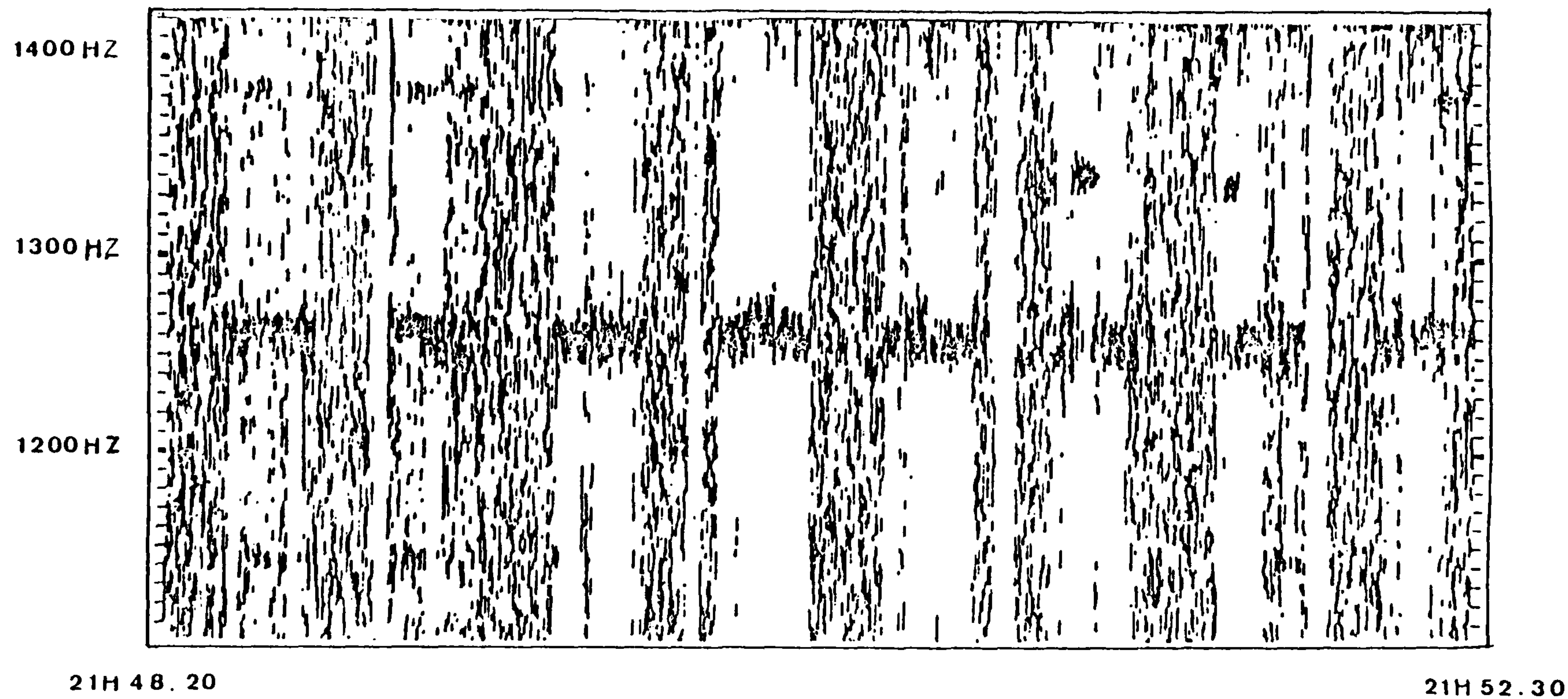

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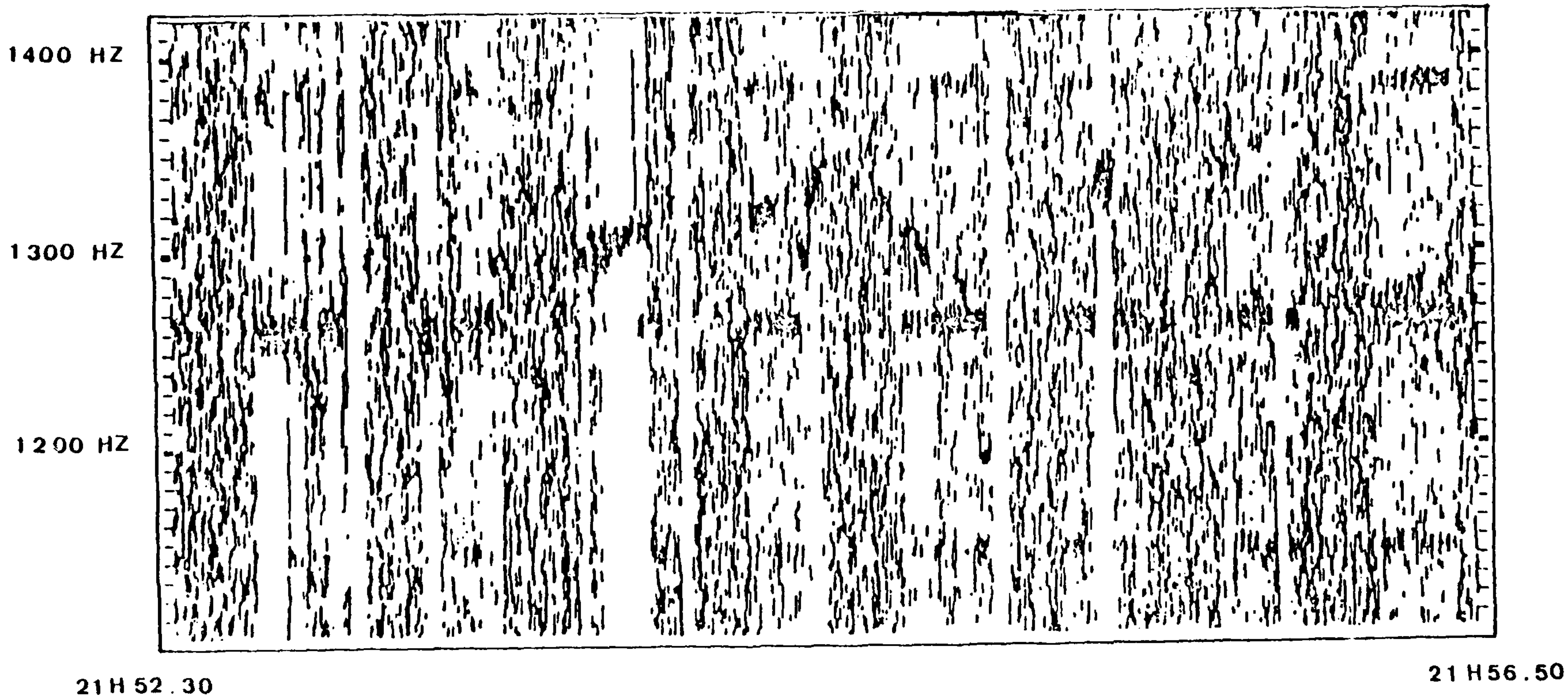
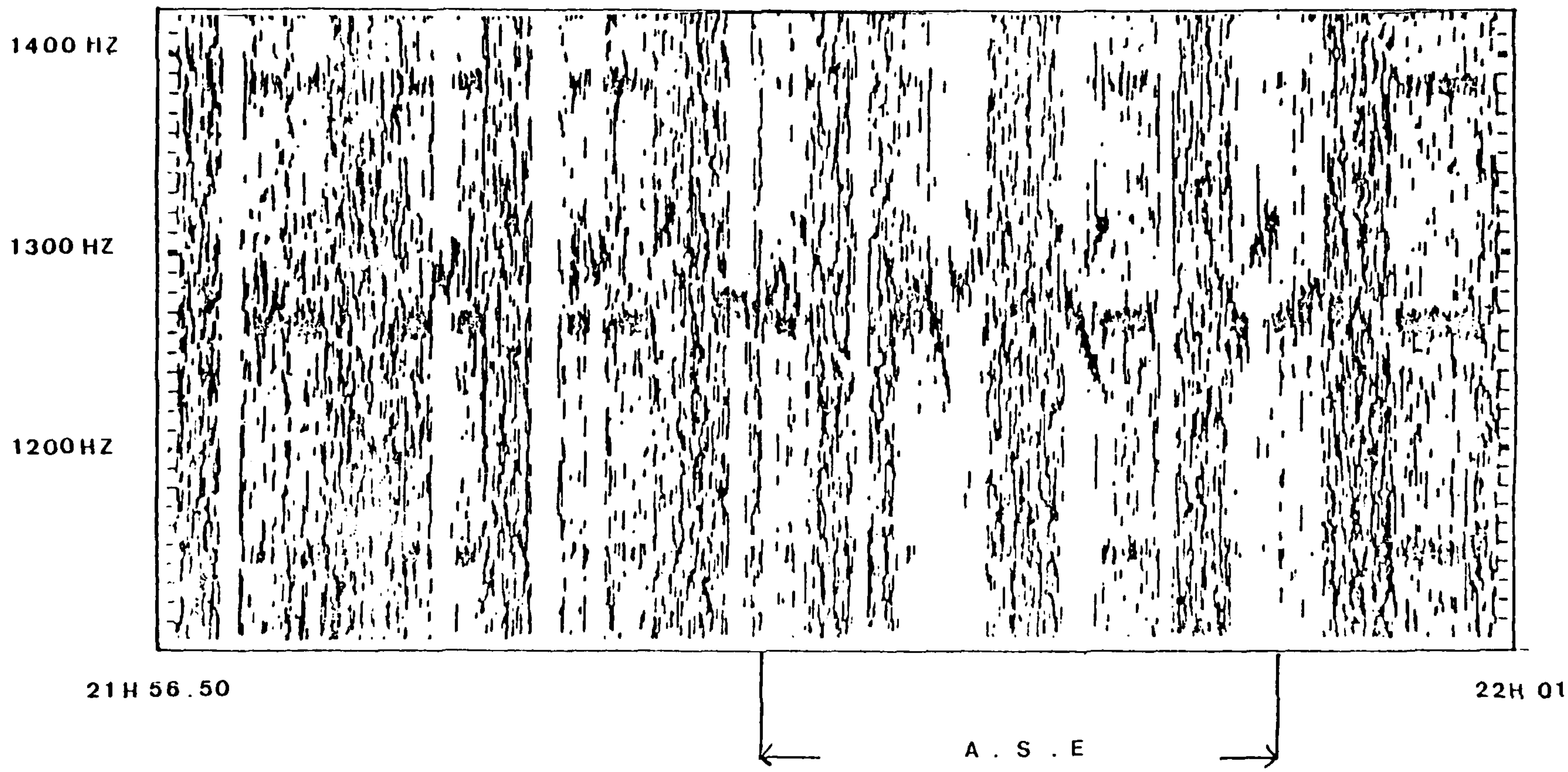
figure 5_c



MAY 27th 1979

figure 5_d



MAY 27th 1979

figure 5 _e

We believe that these emissions have been triggered by our transmissions. The 24 seconds period is correlated with the 12 seconds keying period of our transmissions and can be explained by the fact that - due to the noise level- one signal out of two is not detectable on the magnetic antenna.

Two swept frequency transmissions were detectable - figure 5b between 21.38 UT and 21.40 UT and figure 6c between 21.18 UT and 21.19 UT - and gave rise to steady signals on the swept frequency spectrograms. These emissions are again connected to wave-wave interactions, since while looking at wide band spectrograms one can observe natural signals whose constant frequency is perturbed when the swept frequency becomes close to it.

III - INTERPRETATION

All the emissions reported here are related to wave-wave and wave particles interactions, unfortunately the transmitted wave and its keying were not clearly detected because of the very low transmitted power. So we bring the proof that there is apparently no amplitude threshold for such interactions. Nevertheless one has to take into account the fact that wave particles interactions and consequently triggered emissions are likely to be observed when the wave frequency is nearly equal to half the equatorial gyrofrequency. On May 26th while we were transmitting 1280 Hz at 13.45 UT, the equatorial gyrofrequency on the geostationnary orbit was 2500 KHz. On May 27th this equatorial gyrofrequency was around 2200 Hz. On these two days the condition

$$f_{wave} \simeq \frac{f_{BE}}{2}$$

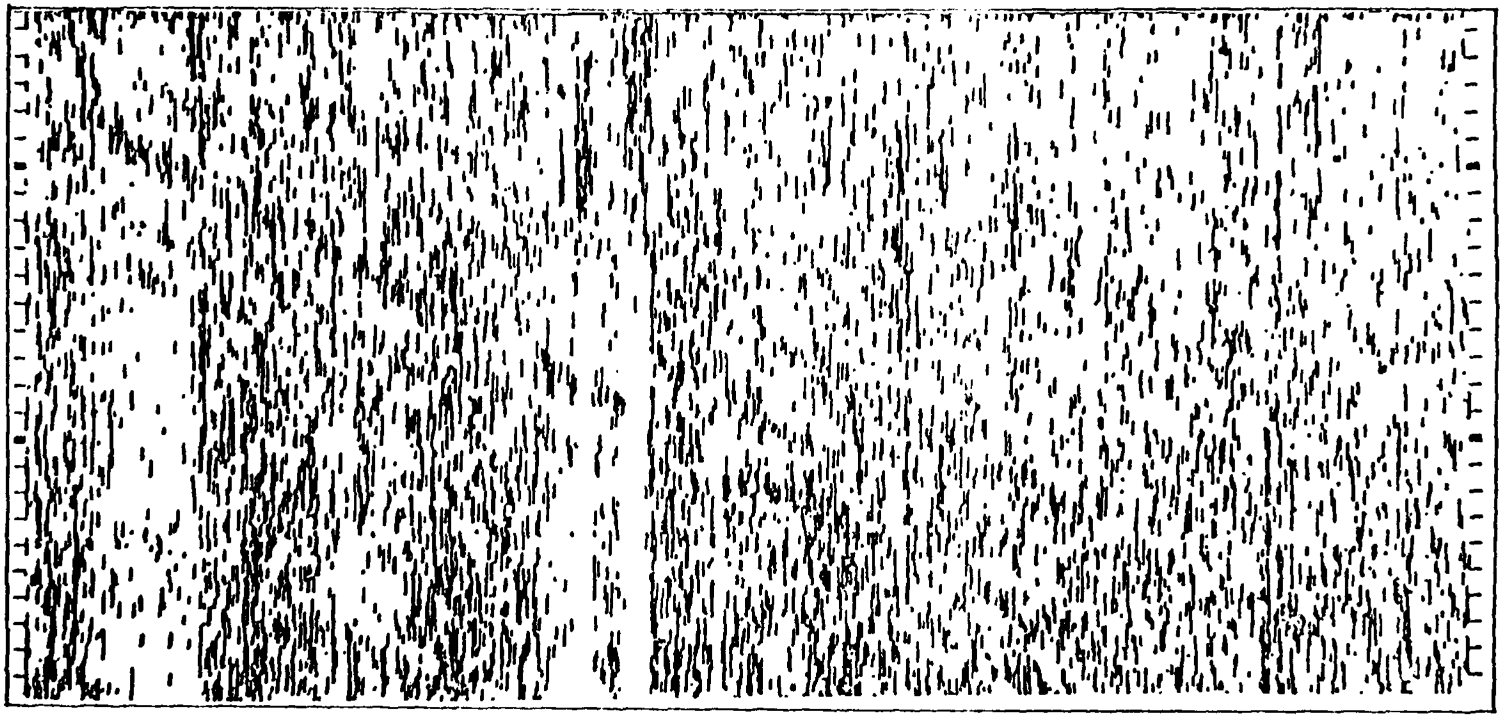
was then satisfied.

The absence of keying on the received signals can be explained by an increase of the magnetospheric processes time constants when the frequency decreases or when the L parameter increases. The phenomenons reported on figures 5d and 5e last at least 10 to 20 times more that the ones reported by Helliwell. In order to prove this hypothesis calculations have to be undertaken, and a slow keying has to be used for further experiments, this was done in May 1980 when the keying code was 20 sec on 20 sec off.

Gliding Window

12.5 HZ per

division



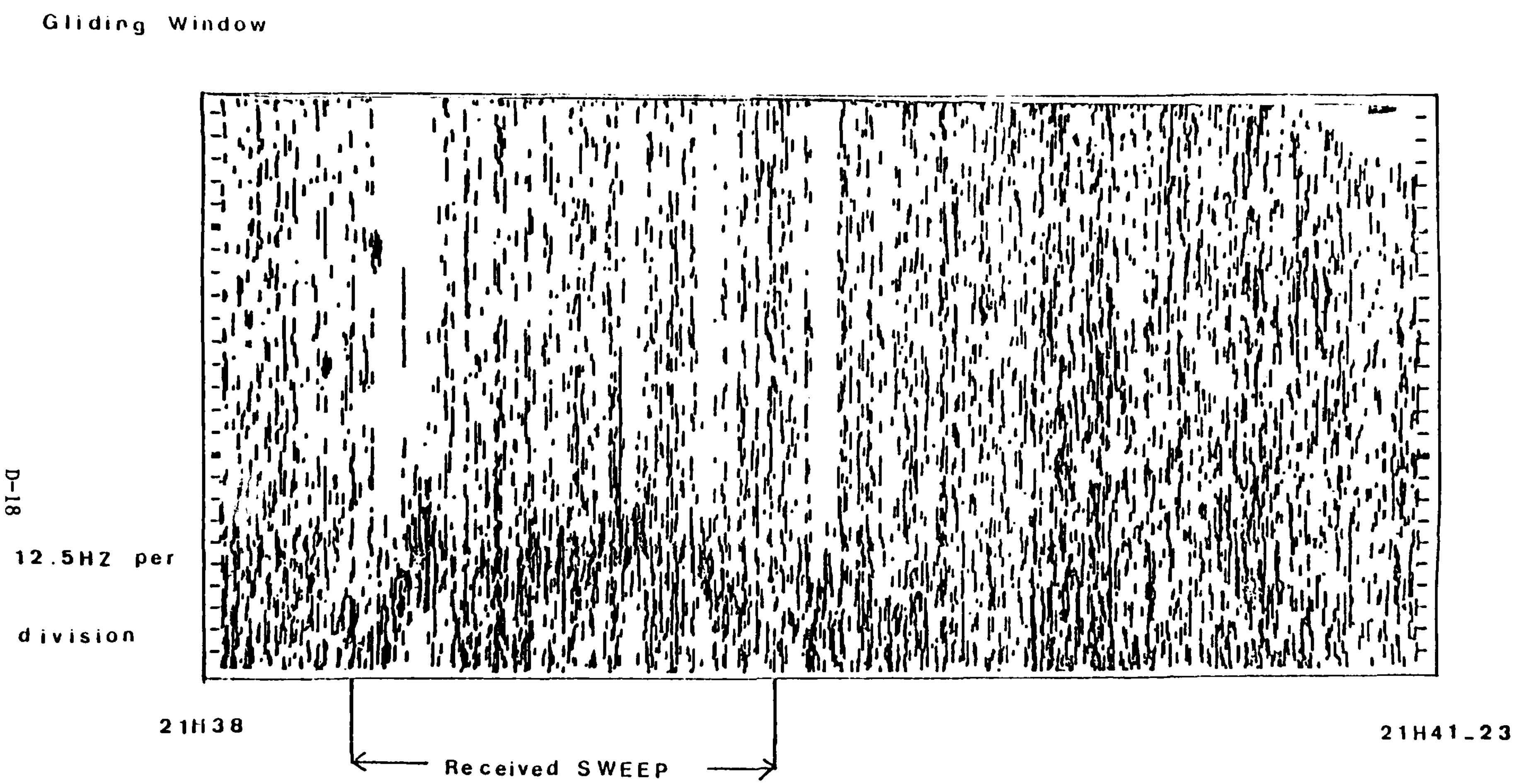
21H34 _30

21H38

SWEEP

MAY 27 th 1979

figure 6_a



MAY 27th 1979

figure 6.b

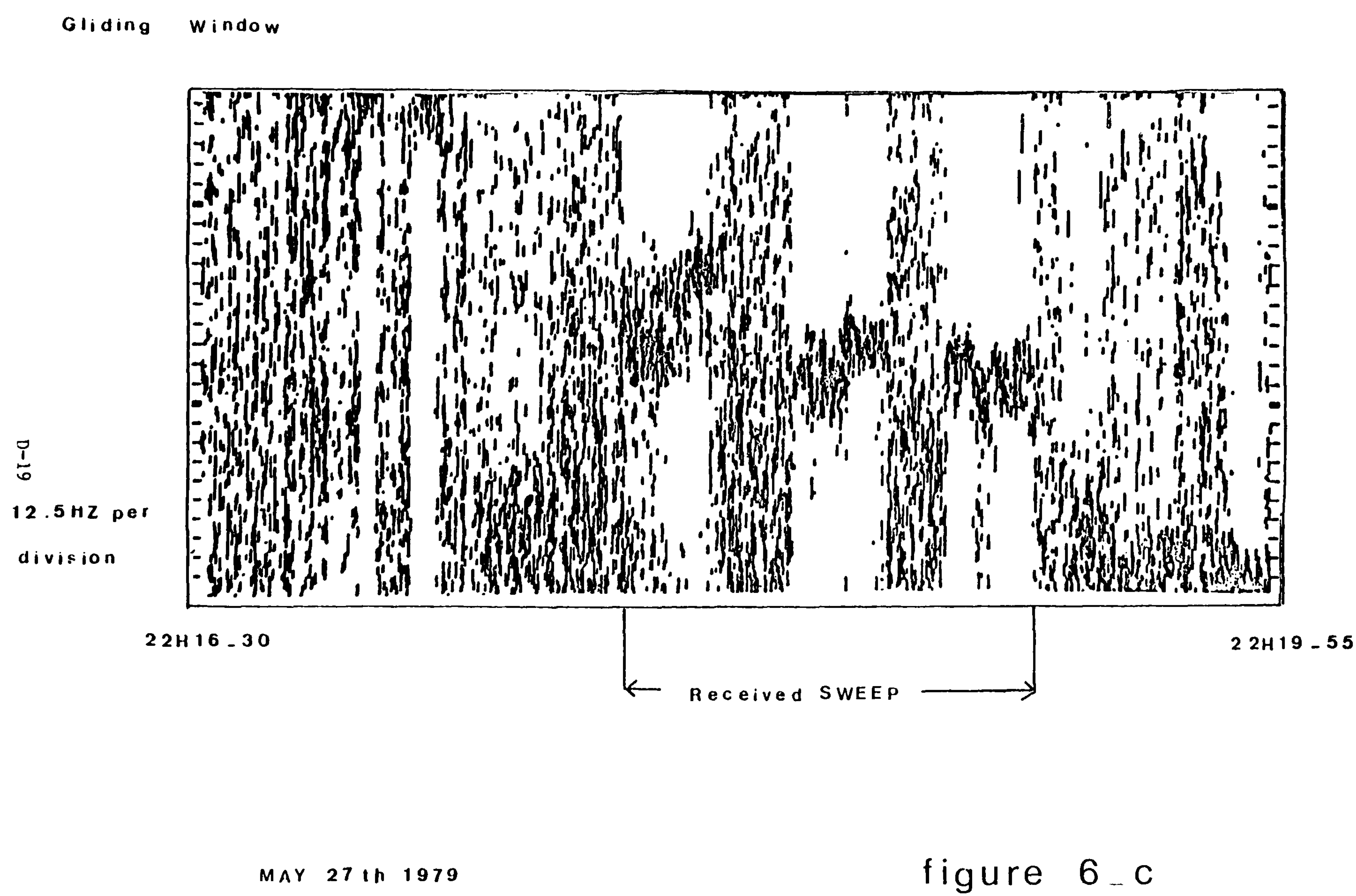
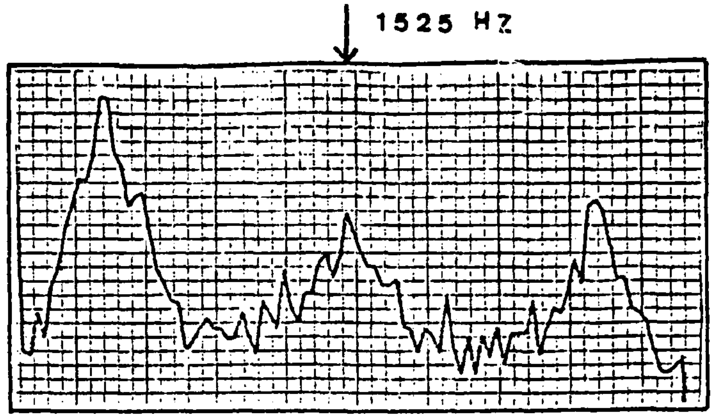

Gliding Window
12.5HZ per
division
22H16_30
22H19_55
Received SWEEP
MAY 27th 1979

figure 6_c

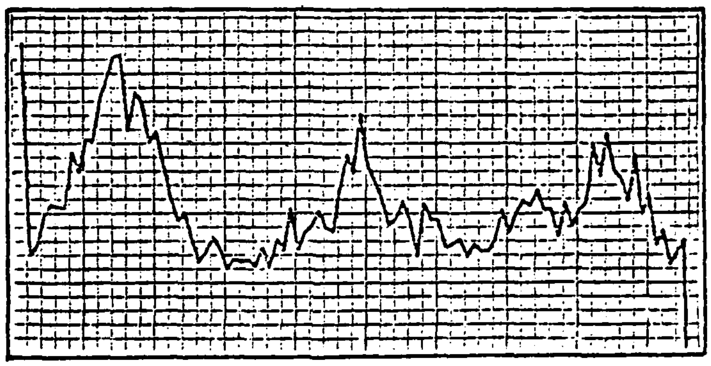
In October 1978 during 1525 Hz transmissions to GEOS the keying code was 10 sec ON and 20 sec OFF, spectrums integrated during 3 ten seconds intervals clearly show on figure 7, the presence of emissions related to the keying during the third period. Further processing of the datas will confirm this preliminary result.

IV - CONCLUSION

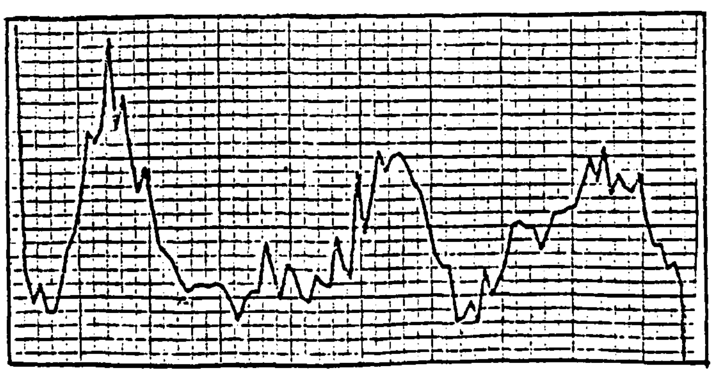
Emissions related to the VLF transmissions were detected on the SCATHA spacecraft receiver, in spite of the very low transmitted power, when the transmitted frequency is close to half the equatorial electron gyrofrequency. There is apparently a very low amplitude threshold for the magnetospheric amplification which was around 15 decibels. The magnetospheric processes time constant seems to increase with the L shell value so that the keying of the transmissions was only detectable while using a slow code.



1st 10 sec period



2nd 10 sec period



3rd 10 sec period

1st october 1978

17H36

GEOS I Integrated Spectrums

figure _7

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LABORATORY OPERATIONS

The Laboratory Operations of The Aerospace Corporation is conducting experimental and theoretical investigations necessary for the evaluation and application of scientific advances to new military concepts and systems. Versatility and flexibility have been developed to a high degree by the laboratory personnel in dealing with the many problems encountered in the Nation's rapidly developing space systems. Expertise in the latest scientific developments is vital to the accomplishment of tasks related to these problems. The laboratories that contribute to this research are:

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